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ATMOSPHERIC OPTICAL TURBULENCE MEASUREMENTS
TAKEN AT
ANDERSON MESA, FLAGSTAFF, ARIZONA
BETWEEN 13-19 NOVEMBER 1989

by

G. Tirrell Vaucher, C.A. Vaucher,
and D.L. Walters

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From 13 to 19 November 1989, the Naval Postgraduate School Atmospheric Optics Group acquired atmospheric optical turbulence measurements at the 31-inch Lowell Observatory telescope dome facility on Anderson Mesa, 16 km southeast of Flagstaff, Arizona. The parameters measured, the transverse coherence length and the isoplanatic angle, were part of an ongoing site survey for a large-scale, ground-based, synthetic aperture system (100-300 m baseline stellar interferometer). This report compiles, analyses and summarizes the acquired optical data. Also discussed are the synoptic meteorological events present during the data acquisition period.

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ABSTRACT

From 13 to 19 November 1989, the Naval Postgraduate School Atmospheric Optics Group acquired atmospheric optical turbulence measurements at the 31-inch Lowell Observatory telescope dome facility on Anderson Mesa, 16 km southeast of Flagstaff, Arizona. The parameters measured, the transverse coherence length and isoplanatic angle, were part of an ongoing site survey for a large-scale, ground-based, synthetic aperture system (100-300 m baseline stellar interferometer). This report compiles, analyses and summarizes the acquired optical data. Also discussed are the synoptic meteorological events present during the data acquisition period.

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We would like to express our sincere appreciation to the Lowell Observatory, particularly Drs. Nat White and Bob Millis (Director), for their assistance during the measurement session and for the use of their 31" telescope dome facility on Anderson Mesa. Also, a special thank you to Nancy Alexander, from Technical and Business Systems, for her many long hours of support with the data acquisition.

I. INTRODUCTION

From 13 to 19 November 1989, the Naval Postgraduate School (NPS) Atmospheric Optics Group acquired atmospheric optical turbulence measurements at the 31-inch Lowell Observatory telescope dome on Anderson Mesa, 16 km southeast of Flagstaff, Arizona. This ensemble of transverse coherence lengths (r_o) and isoplanatic angles (θ_o) was part of an ongoing site survey mission for the Naval Research Laboratory large-scale, ground-based, synthetic aperture system (100-300 m baseline stellar interferometer) and for the NPS-US Air Force optimal site characterization program.

The purpose of this report is three-fold: to document the November 1989 Anderson Mesa optical measurements; to provide a statistical analysis and summary of these optical data; and, to correlate the meteorological activities (using synoptic weather charts) with the optical conditions present during the experiment period. Due to the considerable scale-differential between synoptic weather phenomena (kilometers) and optical turbulence producing events (meters), only a preliminary investigation into the third objective was undertaken. Any detailed correlations would require meso- and micro-scale meteorological information (e.g., high resolution rawinsonde measurements). Such resources were unavailable for this measurement session.

Six appendices supplement this report:

Appendix A presents daily summaries of the synoptic weather conditions prevalent over Anderson Mesa during the optical data acquisition period.

Appendix B contains hand-edited reproductions of the National Weather Service (NWS) 850 and 200 mb synoptic weather charts for the period 13-19 November 1989. For reference, important meteorological features from the NWS surface maps are superimposed onto the 850 mb charts.

Appendix C displays all processed r_o and θ_o data sampled between 13-19 November 1989 Universal Time Coordinated (UTC). Each figure displays a separate night-time session.

Appendices D and E provide nightly, un-normalized percent frequency distributions and empirical seeing quality histograms for r_o and θ_o, respectively. Specific bin intervals for the r_o and θ_o distributions, as well as the empirically derived seeing quality intervals, are listed at the start of each Appendix.

Appendix F presents a cumulative September/November 1989 normalized frequency distribution for both r_o and θ_o. The measurements incorporated in these figures represent all the 17-28 September and 13-19 November 1989 processed NPS optical data taken at both Anderson Mesa and the United States Naval Observatory, Flagstaff, Arizona.

II. EXPERIMENT OVERVIEW

A. SITE TOPOGRAPHY

As described in Vaucher, Vaucher and Walters (1990), Anderson Mesa is an 125 m high plateau situated in the ponderosa pine and lake mesa-country 16 km southeast of Flagstaff and 18 km west of the high desert floor. The 31-inch telescope dome used for optical data gathering is 2.2 km above sea level and located on the southwest edge of the mesa. Figure 1 displays a 3-dimensional topographical view of Anderson Mesa, showing the location of the 31-inch site, as well as major features of interest. The contour interval is 5 meters.

B. DATA ACQUISITION

All data acquisition sessions commenced at local sunset and concluded with the onset of local sunrise twilight. The total sampling duration was approximately 10-11 hours per night. Intermittent cloud-cover often disrupted the ability to sample data, providing both gaps in the individual nightly optical records, as well as severely restricting the total volume of measurements taken during some sessions.

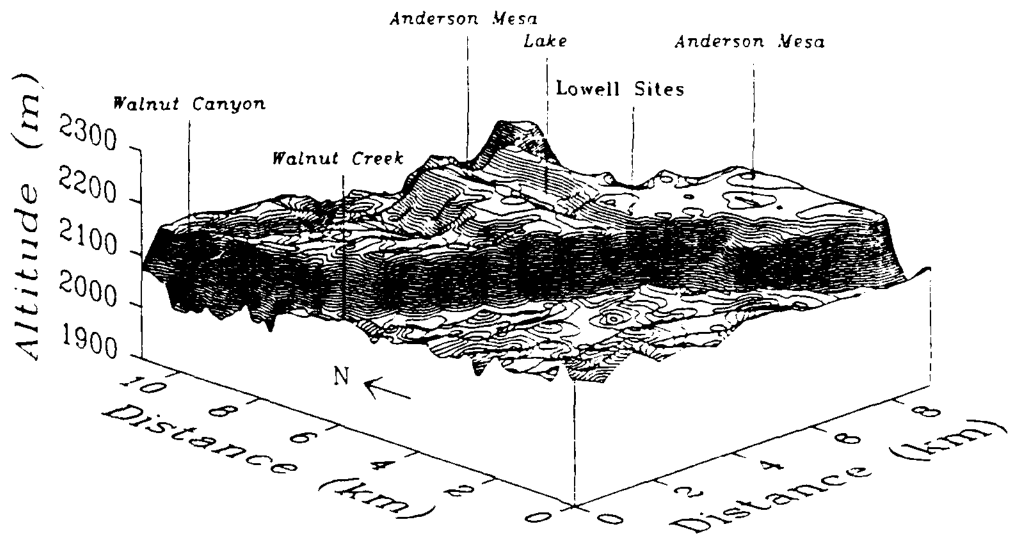
1. Optical Instrumentation and Measurements

The optical turbulence parameters gathered throughout the experiment include the isoplanatic angle (θ_o) and the transverse coherence length (r_o). A brief description of these parameters is available in Vaucher (1989). The isoplanometer and transverse coherence length sensors were designed and built by Dr. D.L. Walters. Stevens (1985) and Walters, Favier, and Hines (1979), respectively describe specific details for each instrument. Vaucher, Vaucher and Walters (1990) explain the optical systems, configurations, and data acquisition procedures utilized during the Anderson Mesa site survey missions.

All optical measurements were recorded in Universal Time Coordinated (UTC). The conversion from local Mountain Standard Time (MST) to UTC is:

$$\text{Time(UTC)} = \text{Time(MST)} + 7 \text{ hours.}$$

Arizona retains MST throughout the year.



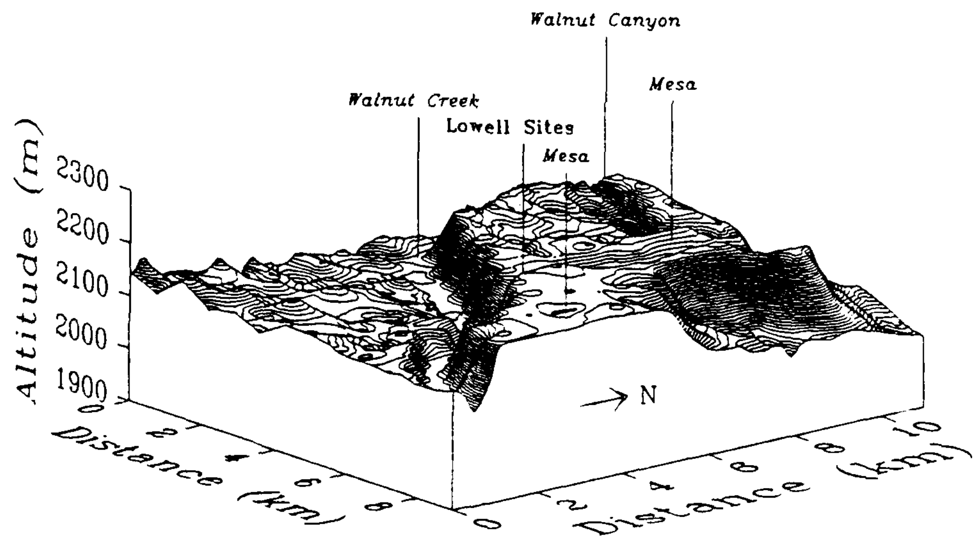


Fig 1. Topographical Views of the Lowell Sites, Anderson Mesa, Arizona

2. Meteorological Surface Data

A model 5165-A WeatherMeasure (WEATHERtronics) Humidity/Temperature Indicator periodically measured the surface meteorological thermodynamic data. Vaucher, Vaucher and Walters (1990) present the detailed specifications for this device. The main function of this probe was to monitor the multiple weather changes and potentially hazardous (extremely cold) environments during the data acquisition.

3. Synoptic Weather Information

GOES-WEST Visible Satellite Images, as well as surface, 500 mb, and 200 mb National Weather Service charts provided an "on-site" evaluation of the synoptic weather conditions. These also helped to detect trends and potential sources of optical turbulence during the experiment period.

Post-experiment analyses of synoptic weather activity around Flagstaff were based on the six National Weather Service standard isobaric charts. These constant pressure surfaces and their equivalent heights are:

Pressure (mb)	Equivalent Height Above Sea Level (km)
Surface	0.1
850	1.4
700	3.0
500	5.5
300	9.2
200	12.0

It should be noted that the equivalent heights indicated above represent average values. For any given pressure level, the actual height will vary as Low and High pressure systems traverse the site (Vaucher, Vaucher, and Walters, 1990). Appendix B provides two of the six NWS isobaric surfaces (850 and 200 mb) used in post-analysis.

III. DATA ANALYSIS

A. OPTICAL DATA ANALYSIS

1. Transverse Coherence Length Data, r_o

Using the Appendix D r_o Empirical Seeing Quality Scale, the dominant r_o optical condition for 13-19 November is mediocre (51-100 mm). Figure 2 displays the oscillatory pattern of average (and standard deviation) r_o as a function of the observing date. Values plotted in this figure are listed in Table 1, along with the nightly r_o standard deviation of the mean. Minimum and maximum average r_o data occur on 15 and 17 November, respectively. November 17 also exhibits the greatest standard deviation of the mean (2.5 mm), but this can be explained: examining the processed data for this date (Appendix C), the initial 5-6 hours of r_o samples are between 51-100 mm; the remaining 5-6 hours are significantly higher (75-275 mm). In contrast, the large standard deviation of the mean calculated for 16 November (2.3 mm) is a function of the limited number of points collected (65 samples).

Figure 3 presents the normalized r_o frequency distributions for each session. These curves generally peak at 100 mm or less, though values above 100 mm are present in all but the 18 November data. The session with the greatest frequency of "good" to "very good" r_o (100 mm and greater) is 17 November 1989 (Table 3).

Compiling all r_o samples acquired between 13-19 November, the cumulative normalized r_o frequency distribution (Figure 4) indicates that 70-80 mm is the interval with the greatest number of samples. Nearly two-thirds (64 %) of all measurements taken have values between 51 and 100 mm ("mediocre").

TABLE 1. TRANSVERSE COHERENCE LENGTH STATISTICS

Date (UTC)	Number of Data Points	Average r_o (mm)	Standard Deviation (mm)	Standard Deviation of Mean (mm)
13 Nov	430	91.6	22.7	1.1
14 Nov	410	77.5	18.3	0.9
15 Nov	351	48.7	13.9	0.7
16 Nov	65	89.3	18.4	2.3
17 Nov	368	101.2	47.3	2.5
18 Nov	241	51.3	11.5	0.7
19 Nov	238	71.2	14.0	0.9

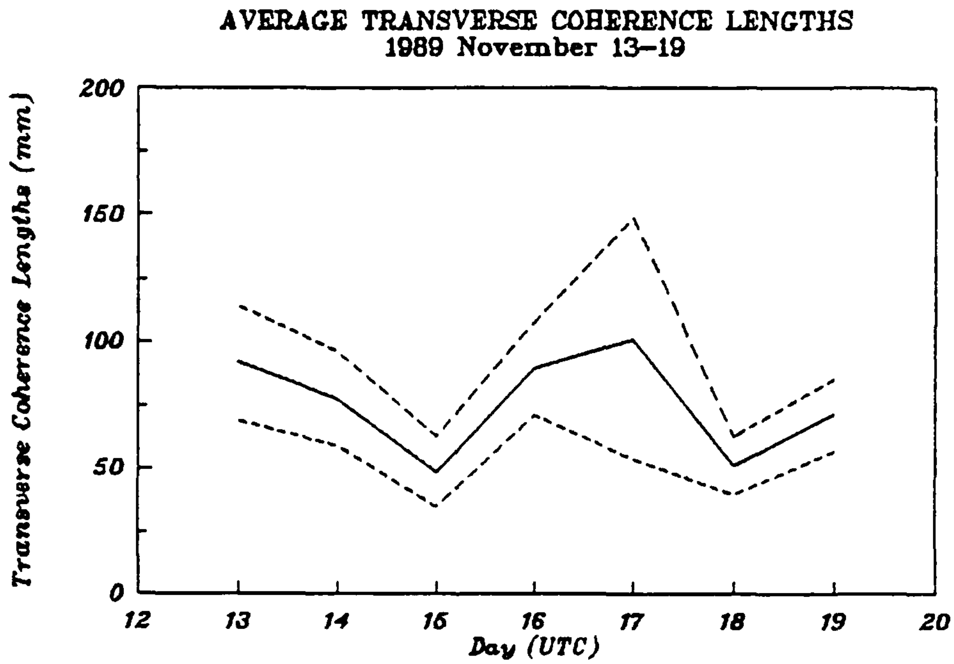
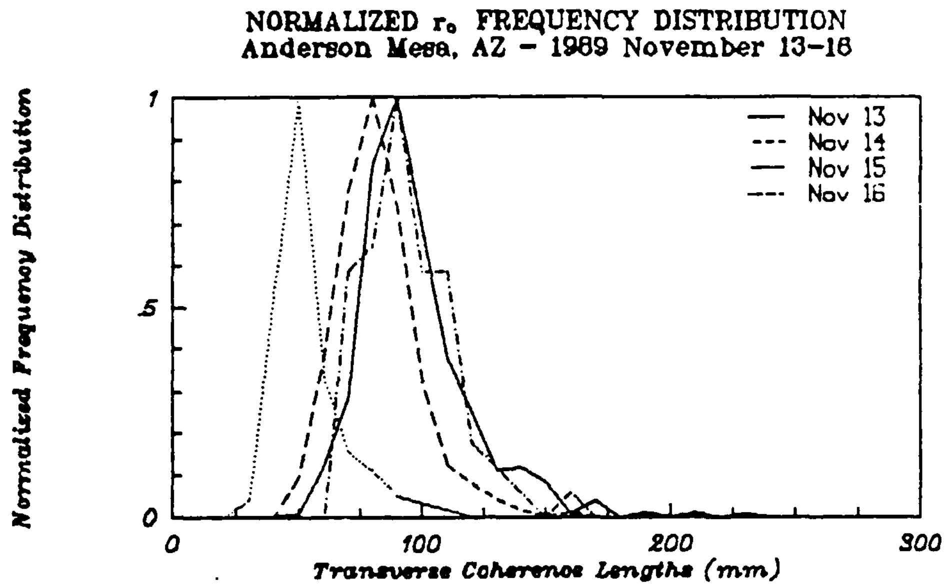


Fig 2. Average Transverse Coherence Lengths (89 Nov 13-19) Solid line is data average; Dashed line is standard deviation of the data.



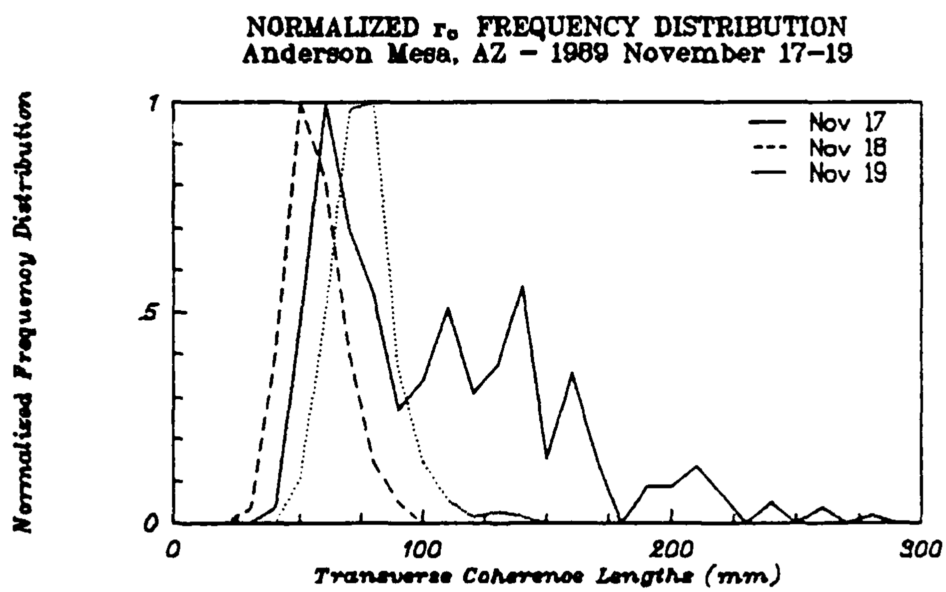


Fig 3. Normalized Transverse Coherence Length Frequency Distributions for Anderson Mesa, Az (1989 Nov 13-19).

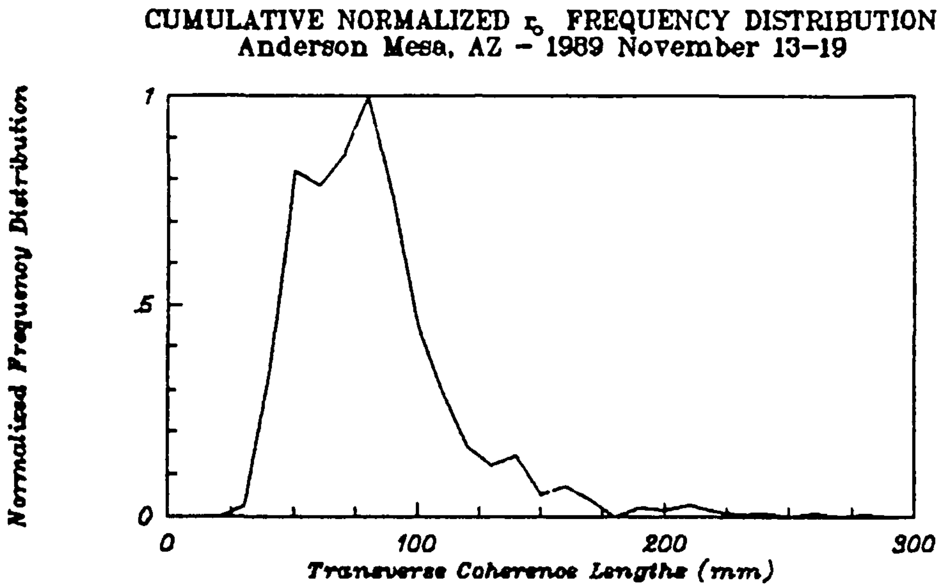


Fig 4. Cumulative Normalized r_o Frequency Distribution for the Anderson Mesa 1989 Nov 13-19 session.

2. Isoplanatic Angle Data, θ_o

Figure 5 shows that the average nightly isoplanatic angles (θ_o) also display an oscillatory pattern. The first order trend for the seven night period is toward smaller angles (more turbulent atmosphere). The average θ_o values (Table 2) begin around 12 urad (13-14 November), then decrease to nearly 6 urad (19 November). θ_o minima occur on 15 and 18 November, with three maxima occurring on 14, 16 and 19 November. While most values are "poor" to "mediocre" (4-12 urad), five of the seven nights display "good" (12-20 urad) optical numbers (see Appendix E for the θ_o Empirical Seeing Quality Scale). The greatest frequency of "good" values (49%) appears on 13 November 1989 (Table 3).

Figure 6 presents the normalized θ_o frequency distributions for each session. The maxima for these curves occur between 3-13 urad. Individual values above 12 urad ("good" to "excellent") are present on 13, 14, and 17 November. The session with the greatest frequency of "good" to "excellent" θ_o is 13 November (Table 3).

Compiling all 13-19 November samples, the cumulative normalized θ_o frequency distribution (Figure 7) has a primary maximum of 4-5 urad, with secondary peaks around 11 and 13 urad. Two-thirds (66%) of all cumulative θ_o samples fall within the range of 0-8 urad ("very poor" to "poor").

TABLE 2. ISOPLANATIC ANGLE STATISTICS

Date (UTC)	Number of Data Points	Average θ_o (urad)	Standard Deviation (urad)	Standard Deviation of Mean (urad)
13 Nov	1029	11.86	1.80	0.06
14 Nov	3643	11.94	2.58	0.04
15 Nov	3129	4.45	0.95	0.02
16 Nov	63	8.46	0.73	0.09
17 Nov	2914	6.07	4.34	0.08
18 Nov	1780	3.19	0.99	0.02
19 Nov	1636	6.19	1.27	0.03

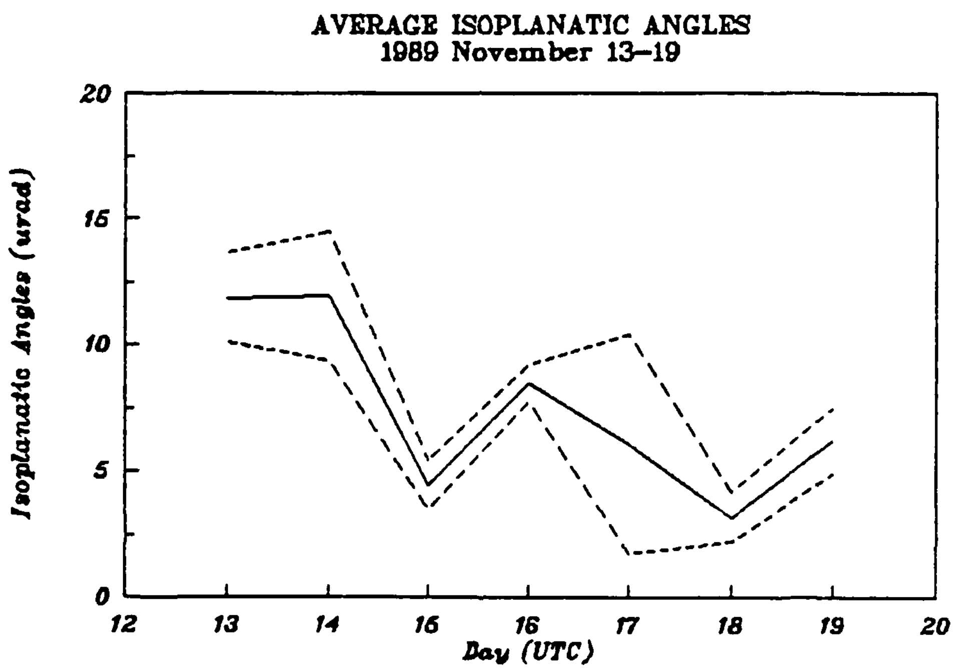
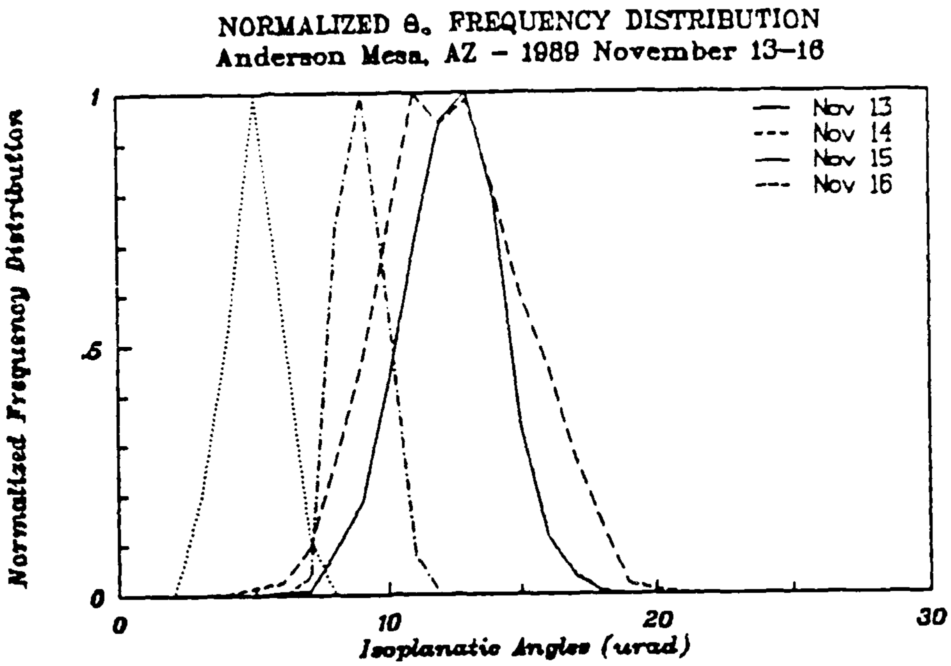


Fig 5. **Average Isoplanatic Angles (89 Nov 13-19)** - Solid line is data average; Dashed line is standard deviation of the data.



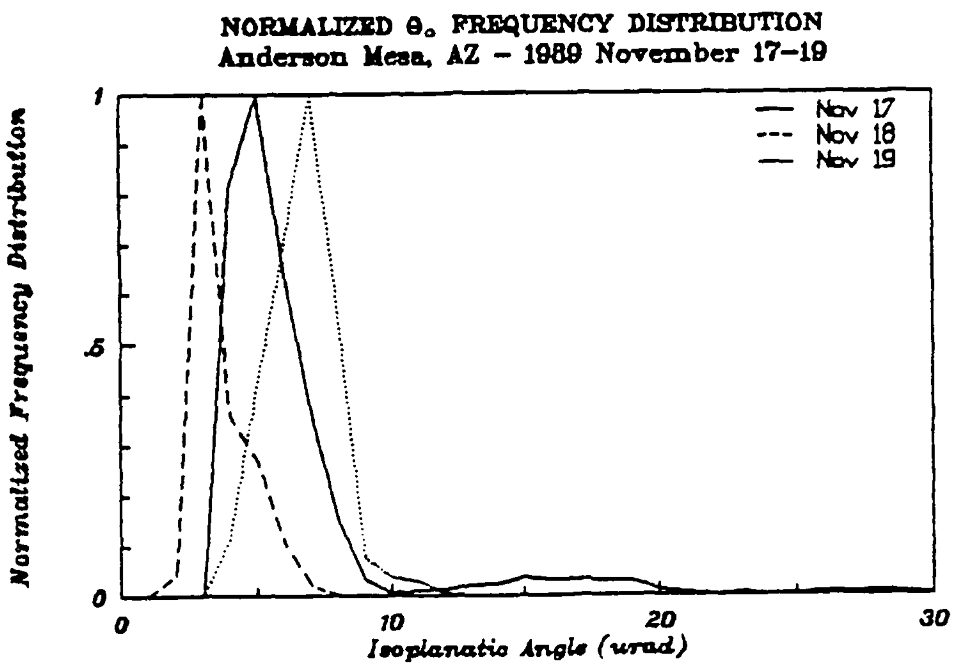


Fig 6. Normalized Isoplanatic Angle Frequency Distributions for Anderson Mesa, Az (89 Nov 13-19).

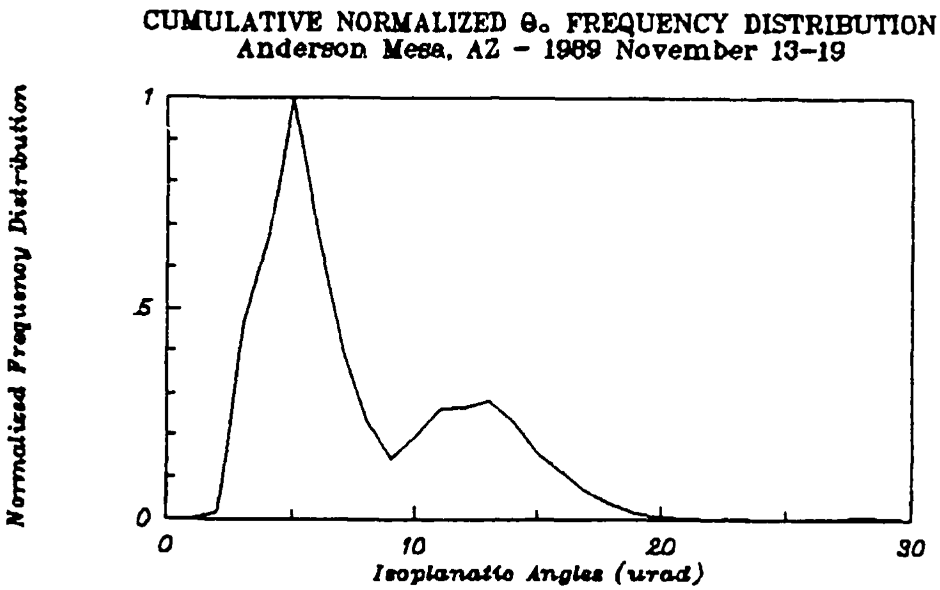


Fig 7. Cumulative Normalized Θ_o Frequency Distribution for the Anderson Mesa 1989 Nov 13-19 session.

B. GENERAL SYNOPTIC WEATHER REVIEW

The overall synoptic weather pattern for the 13-19 November can be categorized into events occurring within three layers:

> From the surface to 700 mb, the northern Pacific High expands eastward over Nevada/Utah. Meanwhile, shortwaves (850- 700 mb) propagate through a mid-continental trough just east of the northern Pacific High.
>
> On the 500 mb level, the site is influenced by the northwesterly circulation associated with the western edge of a mid-continental trough.
>
> Aloft (300-200 mb), polar and subtropical jets (optical turbulence sources) near and overrun the site.

For a day by day review of the synoptic weather activity, see Section IV (Data Summary) and Appendix A. Appendix B provides NWS charts for additional reference.

IV. DATA SUMMARY

A. CONSOLIDATING THE PARAMETERS

Table 3 consolidates key optical and meteorological parameters acquired between 13 and 19 November 1989. While the optical mean values (Parts A and B) appear earlier, the "Empirical % >='Good'" columns are seen for the first time. Here, the Empirical Seeing Quality Scale (Appendices D and E) quantifies the percentage of the individual datum points within an observing session that fall into the "good" or better classifications. The "Empirical Dominant Conditions" columns provide a quick interpretation of typical r_o and θ_o numbers for each night, as calibrated by the empirical seeing quality scale.

TABLE 3. OPTICAL/METEOROLOGICAL SUMMARY-ANDERSON MESA, AZ

A. Transverse Coherence Length:

Nov Date (UTC)	Mean Value (mm)	Empirical: Dominant Conditions	Empirical: % >= "Good"
13	91.6	Mediocre(74%)	25
14	77.5	Mediocre(89%)	8
15	48.7	Poor(69%)	1
16	89.3	Mediocre(74%)	26
17	101.2	Mediocre(46%)	46
18	51.3	Poor(51%)	0
19	71.2	Mediocre(93%)	3

B. Isoplanatic Angle:

Nov Date (UTC)	Mean Value (urad)	Empirical: Dominant Conditions	Empirical: % >= "Good"
13	11.86	Medio/Good(49%)	49
14	11.94	Good(48%)	48
15	4.45	Poor(70%)	0
16	8.46	Mediocre(68%)	0
17	6.07	Poor(65%)	8
18	3.19	Very Poor(78%)	0
19	6.19	Poor(91%)	0

C. Synoptic Meteorological Conditions:

Nov Date (UTC)	Maximum Wind Speed Gradient Horizontal Wind Shear (at 200 mb) ($\times 10^{-5}$) s^{-1}	Frontal(F)/ Non-Frontal(NF)/ Transitional(T)
13	2.6	T
14	1.8	T
15	1.2	F
16	1.7	T
17	2.9	T
18	6.4	T
19	2.1	T

The presence of 200 and 300 mb jet stream flow (70 kt and greater) over a site has been loosely employed as an indicator of turbulence aloft (where θ_o is especially sensitive). To quantify the jet stream activity, the 200 mb NWS synoptic weather chart isotaches were used to calculate the maximum wind speed gradient (200 mb Horizontal Wind Shear) over the site. These results are tabulated in Part C of Table 3.

Another column in the meteorological parameters section (Part C), the "Frontal/Non-Frontal/Transitional", aids in interpreting the potential optical quality over the night. Frontal and Non-frontal weather are as defined in Section IV of Vaucher, Vaucher, and Walters (1990). Generally, Frontal weather produces poor optical conditions while Non-Frontal weather renders a stable atmosphere of generally high optical quality. Transitional implies a changeover period from either Frontal or Non-Frontal conditions. It often signifies an atmosphere in which separate cold and warm air masses collide and mix, frequently producing very turbulent layers and subsequently poor optical seeing.

B. OPTICAL/METEOROLOGICAL DATA CORRELATIONS

The following discussion assimilates the various important elements presented in the Data Analysis Section (Part III) and, Appendices A through E. Table 3 should be referenced throughout.

The initial two nights (13-14 November) of optical data collection were predominantly "mediocre" for both r_o and θ_o. Synoptic weather activity over this time period included a turbulence-inducing shortwave in the 850-700 mb pressure layer, as well as a mid-to-upper level (500-200 mb pressure layer) Low centered over the Mexico/Arizona border. Wind shear aloft was magnified with the approach of accelerated airflows (70 knot jets) to the north and south.

The smallest r_o and θ_o values measured (most turbulent conditions) were sampled on 15 November 1989. Initially (0100 UTC), r_o were centered around 90 mm. Later that night, the values decreased to approximately 40 mm (0400 to 1230 UTC). The θ_o values went from poor (4-8 urad) to very poor (0-4 urad) during the same time period. The overall wretched optical conditions were a product of a variety of turbulence producing events: a cold front traversing the

site; a transition from an eastward moving Low to the clockwise circulation of the northern Pacific High spreading over Nevada; and, an approaching 70-110 kt jet aloft.

Seeing conditions, as measured by r_o, gradually improved over the next two nights (16-17 November). Note that on 16 November, sampling was severely restricted due to an extensive cloud cover. Hence, statistics derived from this limited session should be cautiously considered.

On 17 November, 46% of the r_o samples measured were between 101-300 mm ("good" to "very good"), 46% were between 51-100 mm ("mediocre") and 8% were between 0-50 mm ("poor") (Appendix D). The θ_o values indicated turbulence aloft: 8% were between 12-20 urad ("good"), while the remaining 92% were between 0-11 urad ("very poor" to "mediocre") (Appendix E). The transitional synoptic events producing these contrasting r_o and θ_o measurements included: an eastern extension of the northern Pacific High competing with a Low over Mexico. During this period, the High dominated. Aloft, however, a 70-110 kt jet flowed counterclockwise within 5-8 degrees latitude (555-888 km) of the site. Though synoptic weather charts indicate that the jet did not traverse the site, the shear set up by the proximity of the jet flow was enough to suppress the isoplanatic angles.

In the last two sessions (18-19 November), r_o dipped to an average value of 51 and 71 mm (both "mediocre"), respectively. The corresponding average θ_o were 3 and 6 urad ("very poor"/"poor"). The synoptic weather scenario for 18 November continued to be transitional (Table 3). The site was under a southeastward moving surface High centered in the northwestern states and a surface Low over Mexico. At 850 mb, the site was on the edge of the northern Pacific High extension and a flow through the mid-continental trough. From 700-500 mb, an eastward moving shortwave placed the site under a weak Low. This Low became more organized between 0000 and 1200 UTC. Aloft, a 70 to 110 kt jet initially (0000 UTC) circumnavigated the site, passing within 5-8 degrees latitude in all directions. By 1200 UTC, a 115 kt northwesterly jet passed over the mesa at 200 mb. Wind shear for the 200 mb level began at 4.3E-5 s^{-1} (0000 UTC) and increased to 8.5E-5 s^{-1} (very strong shear!!) by 1200 UTC. This pattern of strong wind shear often results in low optical turbulence numbers. The 18 November measurements reinforced this general observation.

On 19 November 1989, the synoptic weather pattern over the site included a High pressure system associated with the northern Pacific High extending over Utah. The presence of this High was observed from the surface to 500 mb. At 500 mb, the site bordered the High just described above, and a Low over Baja, California. Aloft, the site was directly under a jet supporting a Low over Mexico. During the 0000-1200 UTC time interval, this upper level Low appeared to develop as a cut-off Low over Mexico/southwestern states. Wind shear over the site at 200 mb was about 2.1E-5 s^{-1} ; slightly weaker than 18 November, yet still a significant element for optically turbulent conditions aloft (low θ_o values).

The greatest 200 mb horizontal wind shear occurred on 18 November. Also on this date, the mean θ_o was the smallest magnitude of the seven day session, with dominant conditions empirically classed as "very poor" (78%). The 18 November mean r_o likewise registered a low magnitude (51.3 mm), with the dominant conditions rated as "poor" (51%). Unfortunately, the least turbulent conditions measured by the optical parameters do not coincide with the smallest 200 mb wind speed gradient. Since optical turbulence is a function of both the three-dimensional wind shear and temperature gradient integrated through an entire atmospheric cross-section, a good correlation between a single level horizontal wind shear (e.g., 200 mb) and the general optical conditions cannot be expected.

V. CONCLUSIONS/RECOMMENDATIONS

The primary purpose of this study was to evaluate the Flagstaff, Arizona region as a potential site for a large baseline stellar interferometer. The initial measurement session completed in September 1989 by the Atmospheric Optics Group (NPS) found that "despite the constant colliding of cold and warm air masses typical for this area in September, significant Good to Excellent seeing conditions occurred". (Vaucher, Vaucher, Walters, 1990)

In contrast to September 1989, the November 1989 measurement session yielded only limited "good" quality optical data. The fragmented layers of contrasting air masses (a predominantly transitional weather pattern), coupled with an accelerated circulation (jet) over the site (300-200 mb), rendered an almost continuously turbulent optical environment. A glimmer of favorable atmospheric optical conditions occur on 13-14 November for θ_o and 17 November for r_o. Because the data discussed throughout the previous sections are only a snapshot of the true atmospheric optical conditions over Anderson Mesa, the original September 1989 site report recommendation remains: for an ideal optical database, one should take samples every night for several years. More realistically, the authors propose acquiring a seasonal 7-10 night optical dataset coupled with a climatological study of the site. To attain a better understanding of the events producing the measured optical conditions, a minimum of three on-site, high resolution, rawinsonde launches per observation night are recommended.

In summary, the Flagstaff region warrants further consideration. It must be examined seasonally, for at least one to two years more before crude conclusions as to its optical viability can be determined.

APPENDIX A. DAILY SYNOPTIC WEATHER SUMMARY

Site: Anderson Mesa, Flagstaff, Arizona
Time Period: 13-19 November 1989 (UTC)
Equipment Used: Transverse Coherence Length Sensor
Isoplanatic Angle Sensor
National Weather Service Synoptic Charts

The overall synoptic weather pattern for the 13-19 November 1989 time period consists of:

surface-700 mb:	The northern Pacific High expanding eastward over Nevada/Utah;
850-700 mb:	Shortwaves propagating through a mid-continental trough;
500 mb:	The western edge of a mid-continental, longwave trough dictating the circulation pattern;
300-200 mb:	Polar/subtropical jets (source of optical turbulence) nearing/overrunning the site.

The "worst" seeing was sampled on 15 November 1989. Transverse coherence lengths began around 90 mm 0100 UTC), then decreased to approximately 40 mm (0400 to 1230 UTC). Isoplanatic angles went from poor (4-8 urad) to very poor (0-4 urad) during the same time period. The overall wretched optical conditions were a product of a cold front traversing the site coupled with an approaching 70-110 knot (kt) jet aloft.

The "best" seeing was measured on 17 November 1989. Transverse coherence lengths were generally between 100-250 mm from 0600 to 1045 UTC. The isoplanatic angles during this time period, however, were poor (4-8 urad). The major synoptic events creating these apparently dichotomous optical measurements may be explained by the presence of a High pressure center dominating conditions, with a (wind) jet aloft. Specifically, an eastern extension of the northern Pacific High was competing with a Low over Mexico. During this session, the High dominated. Aloft, however, a 70-110 kt jet flowed counterclockwise within 5-8 degrees latitude (555-888 km) of the site. Though the synoptic weather charts indicate that the jet does not traverse the site, the shear set up by the proximity of the jet was enough to suppress the isoplanatic angles.

DAY BY DAY SYNOPTIC WEATHER SUMMARY

ANDERSON MESA, FLAGSTAFF, ARIZONA (1989)

Dates: 12 Nov, 2015 hrs - 19 Nov, 0000 hrs (local time)
13 Nov, 0315 hrs - 19 Nov, 0700 hrs (UTC)

13 November 1989: The synoptic weather pattern over the site is characterized by a surface High; a shortwave propagating through a mid-continental trough (850 mb). At the 700 mb level, the circulation is dictated by the western edge of the mid-continental, longwave trough. From 500 to 200 mb, a Low centered over the Mexico/Arizona border dominates the circulation. By 1200 UTC, this cutoff Low merges with the mid-continental trough (300 mb level).

14 November 1989: The synoptic weather pattern over the site continues with a surface High; a weak shortwave propagating through the mid-country trough (850-700 mb). At 500 mb, the site is west of the longwave trough traversing mid-country. Aloft (0000 UTC), the site is south of a southward moving mid-country trough. By 1200 UTC, the approaching trough moves a 70 kt jet within 5-8 degrees latitude north and south of the site.

15 November 1989: Synoptic weather conditions include a surface 'trof' passing over the site (0000 UTC) with a cold front just to the north. By 1200 UTC, the cold front is located slightly south of the site. At the 850 mb level, the site transitions from the western edge of the mid-country Low (0000 UTC) to the clockwise circulation of the northern Pacific High spreading over Nevada. The 700-500 mb level is dominated by the northwesterly flow around the mid-country trough. Aloft (300-200 mb), a 70-110 kt west-northwesterly jet passes within 2-4 degrees latitude (on all except the southwestern side) of the site.

16 November 1989: Extensive cloud cover limits the optical data sampling. Limited synoptic wind data is available for this session. From 850 to 300 mb, the site is under the western edge of the mid-country trough; the North Pacific High extends over Nevada (850 mb). At 200 mb, the 70-110 kt jet is within 5-8 degrees latitude northwest and southeast of the site.

17 November 1989: The site borders a southeastward moving surface High centered in Oregon and a surface Low over Mexico. Between 850 and 700 mb, the site is on the edge of the extended northern Pacific High/mid-continental trough. At 500 mb, an eastward moving shortwave puts the site under a weak Low. Aloft, a 70 to 110 kt jet is within 5-8 degrees latitude northwest, west and southeast of the site. Though the jet does not traverse the site, the shear set up by the jet's location is enough to suppress the isoplanatic angles.

18 November 1989: The synoptic weather scenario places the site under a southeastward moving surface High centered in the northwestern states and a surface Low over Mexico. At 850 mb, the site is on the edge of the northern Pacific High extension and a flow through the mid-continental trough. From 700-500 mb, an eastward moving shortwave places the site under a weak Low. This Low organizes between 0000 and 1200 UTC. Aloft, a 70 to 110 kt north-northeasterly jet circumnavigates the site (passing within 5-8 degrees latitude). Though the jet does not initially traverse the site, the 200 mb shear set up by the 0000 UTC pattern is approximately 4.3E-5 s^{-1} . By 1200 UTC, a 115 kt northwesterly jet passes over the site. The 200 mb wind shear consequently increases to about 8.5E-5 s^{-1} (very strong shear!!).

19 November 1989: The synoptic weather pattern includes a High pressure system associated with the northern Pacific High extending over Utah. The presence of this High is observed from the surface to 500 mb. At 500 mb, the site borders the High just described and a Low over Baja, California. Aloft, the site is directly under a 70-90 kt northeasterly jet supporting a Low over Mexico. During the 0000-1200 UTC time interval, this Low appears to develop as a cut-off Low over Mexico/southwestern United States. Wind shear over the site at 200 mb (0000 and 1200 UTC) is about 2.1E-5 s^{-1} ; weaker than 18 November, yet still significant.

APPENDIX B. NWS 850 AND 200 MB SYNOPTIC WEATHER CHARTS

The following National Weather Service (NWS) 850 and 200 mb isobaric weather charts display the synoptic activity present during the 13-19 November 1989 UTC optical measurement session. A plus symbol identifies the location of the Anderson Mesa (Flagstaff, AZ) data collection site. Surface fronts, as well as surface High and Low pressure systems (circled "H" and "L" labels) have been superimposed onto the 850 mb charts. Dashed lines on the 200 mb charts trace the jet stream activity. Specifically, the dashed lines outline the 70 kt isotaches, as well as the labelled jet streak maxima (generally, 110 kt or greater).

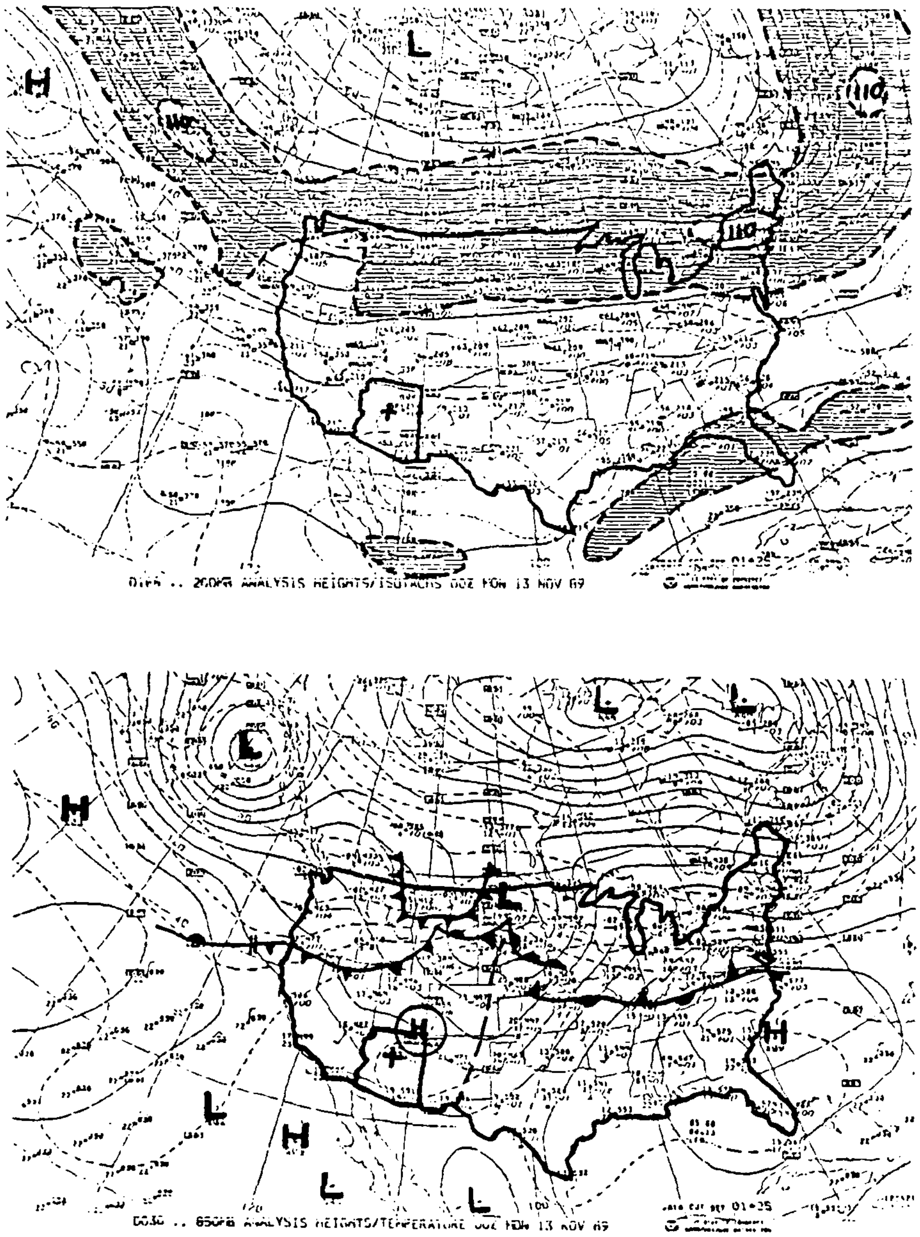


Fig 8. NWS 850 (bottom) and 200 (top) mb Charts: November 13, 0000 UTC

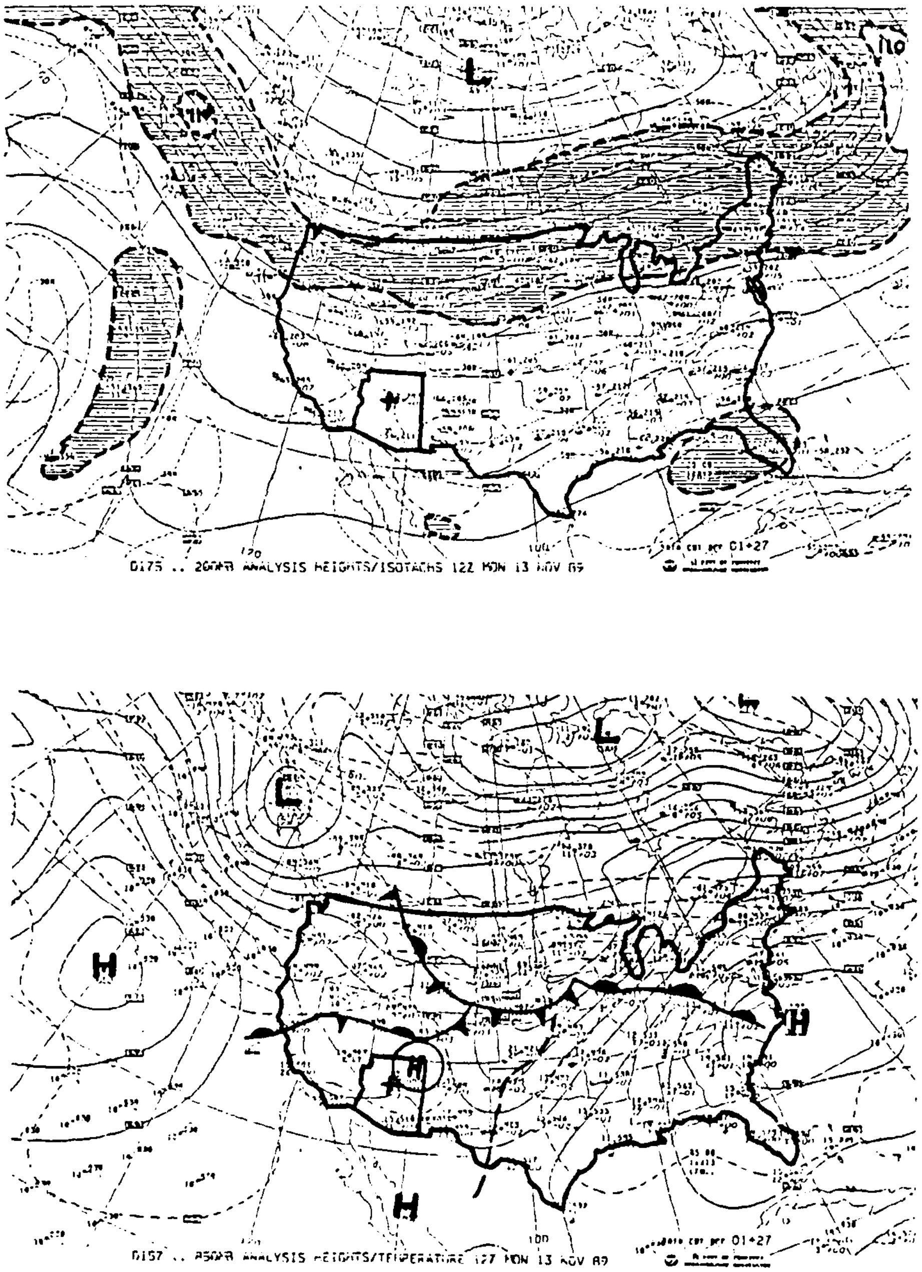


Fig 9. NWS 850 (bottom) and 200 (top) mb Charts: November 13, 1200 UTC

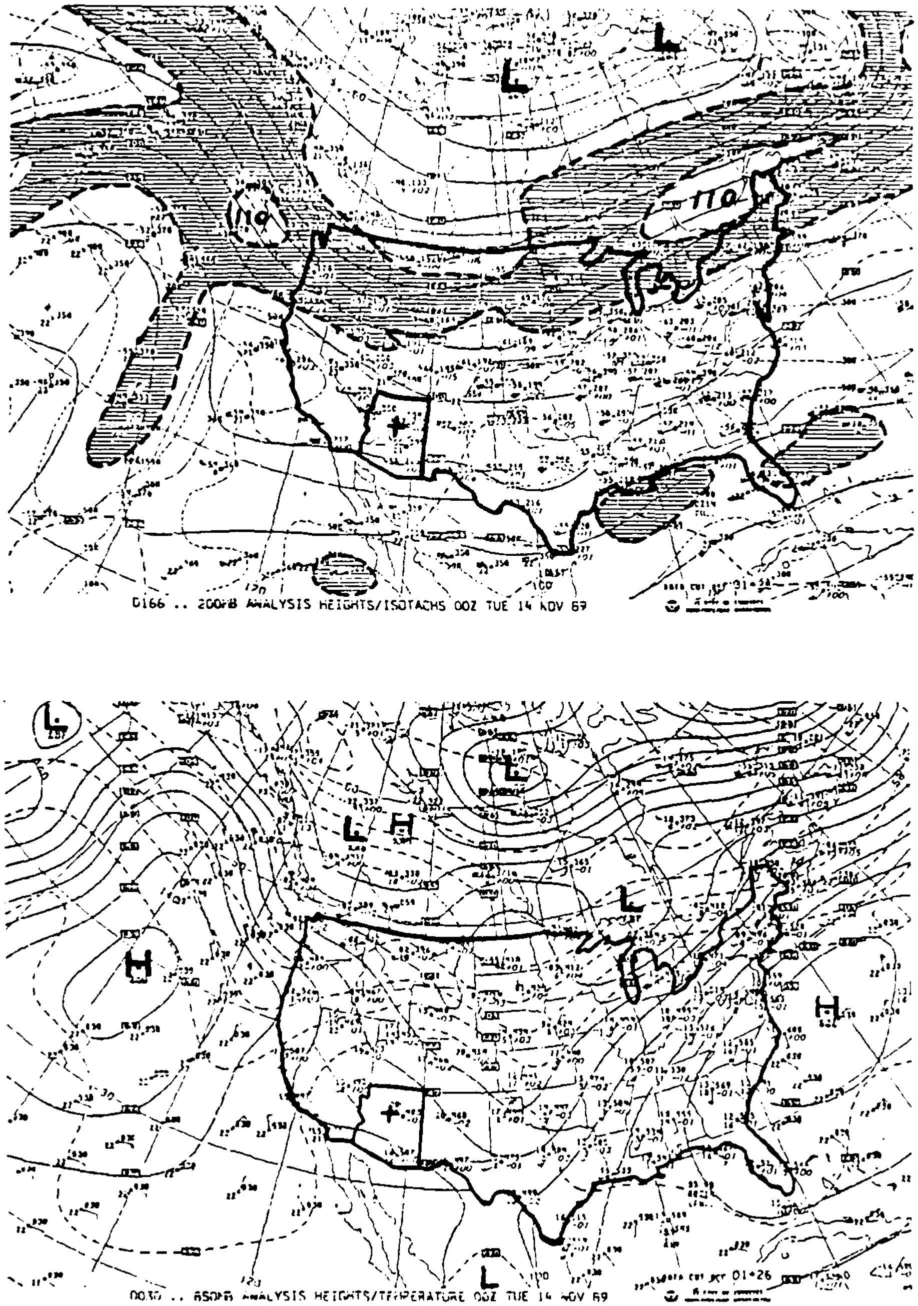
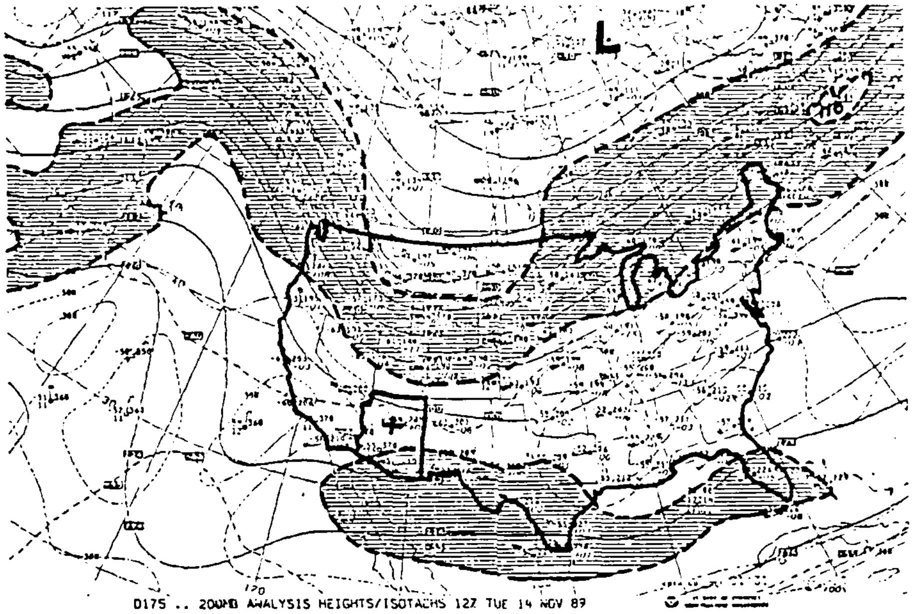


Fig 10. NWS 850 (bottom) and 200 (top) mb Charts: November 14, 0000 UTC



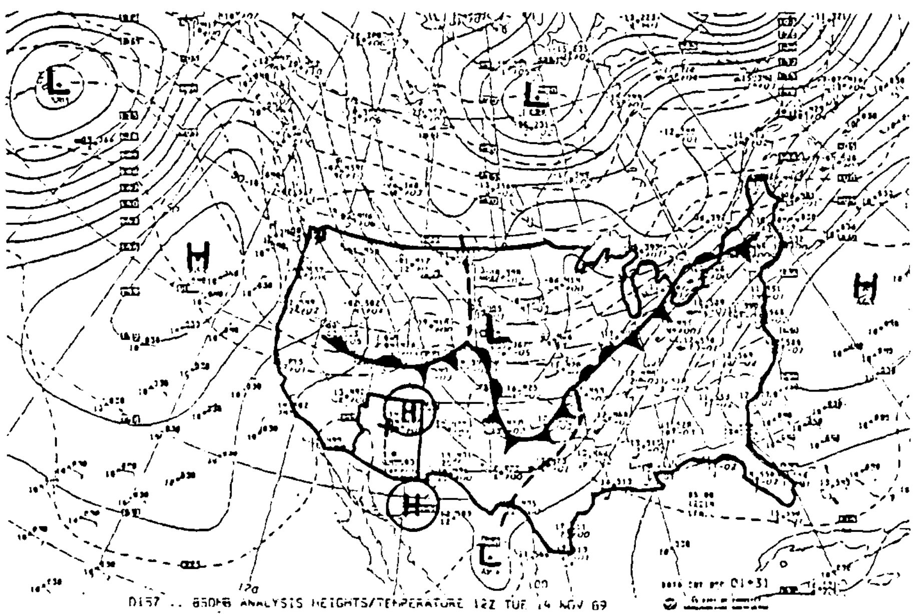
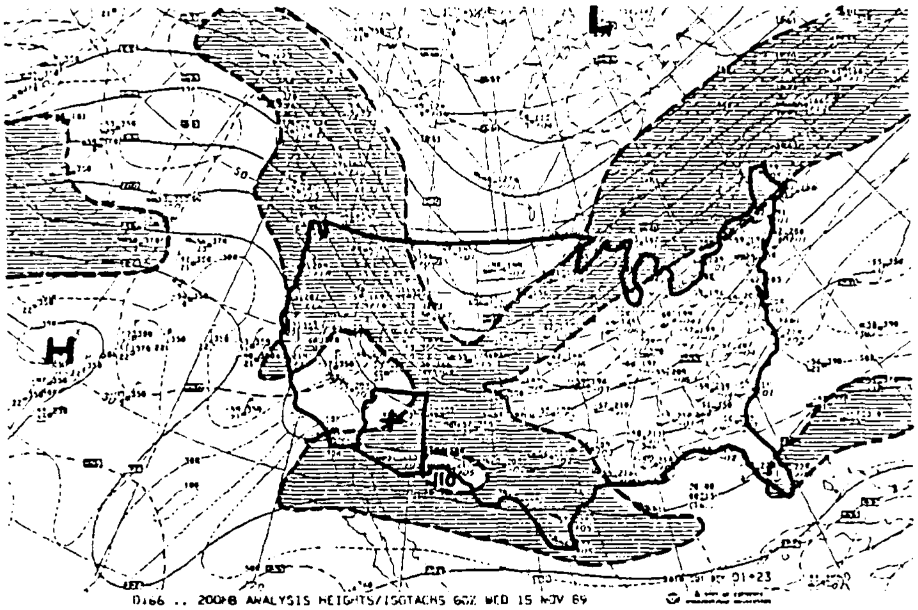


Fig 11. NWS 850 (bottom) and 200 (top) mb Charts: November 14, 1200 UTC



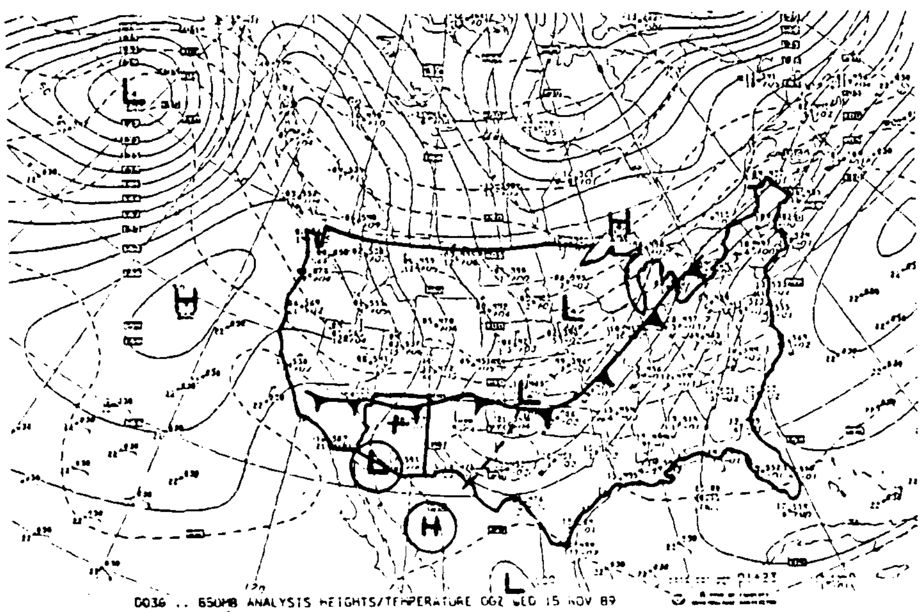


Fig 12. NWS 850 (bottom) and 200 (top) mb Charts: November 15, 0000 UTC

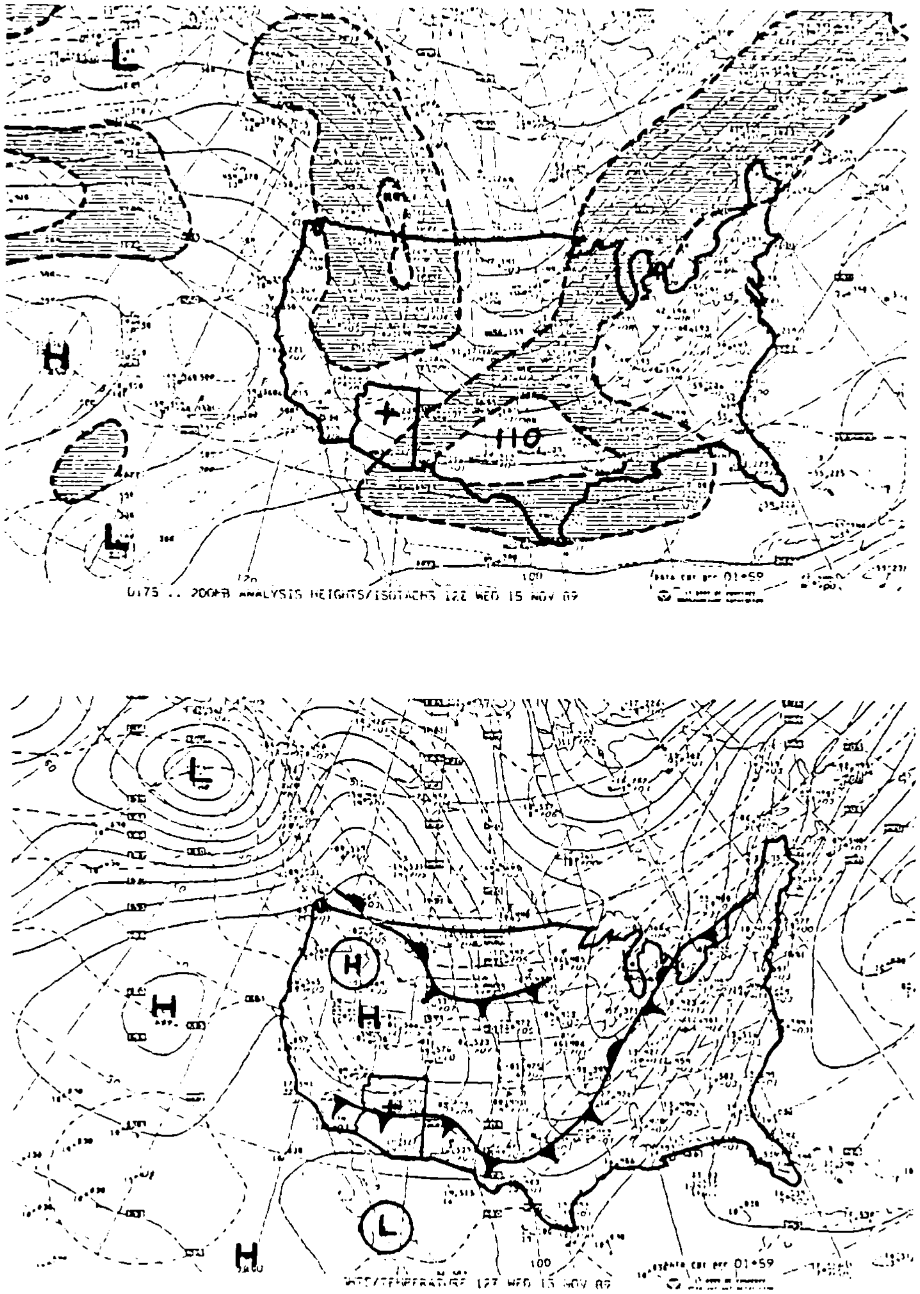


Fig 13. **NWS 850** (bottom) **and 200** (top) **mb Charts: November 15, 1200 UTC**

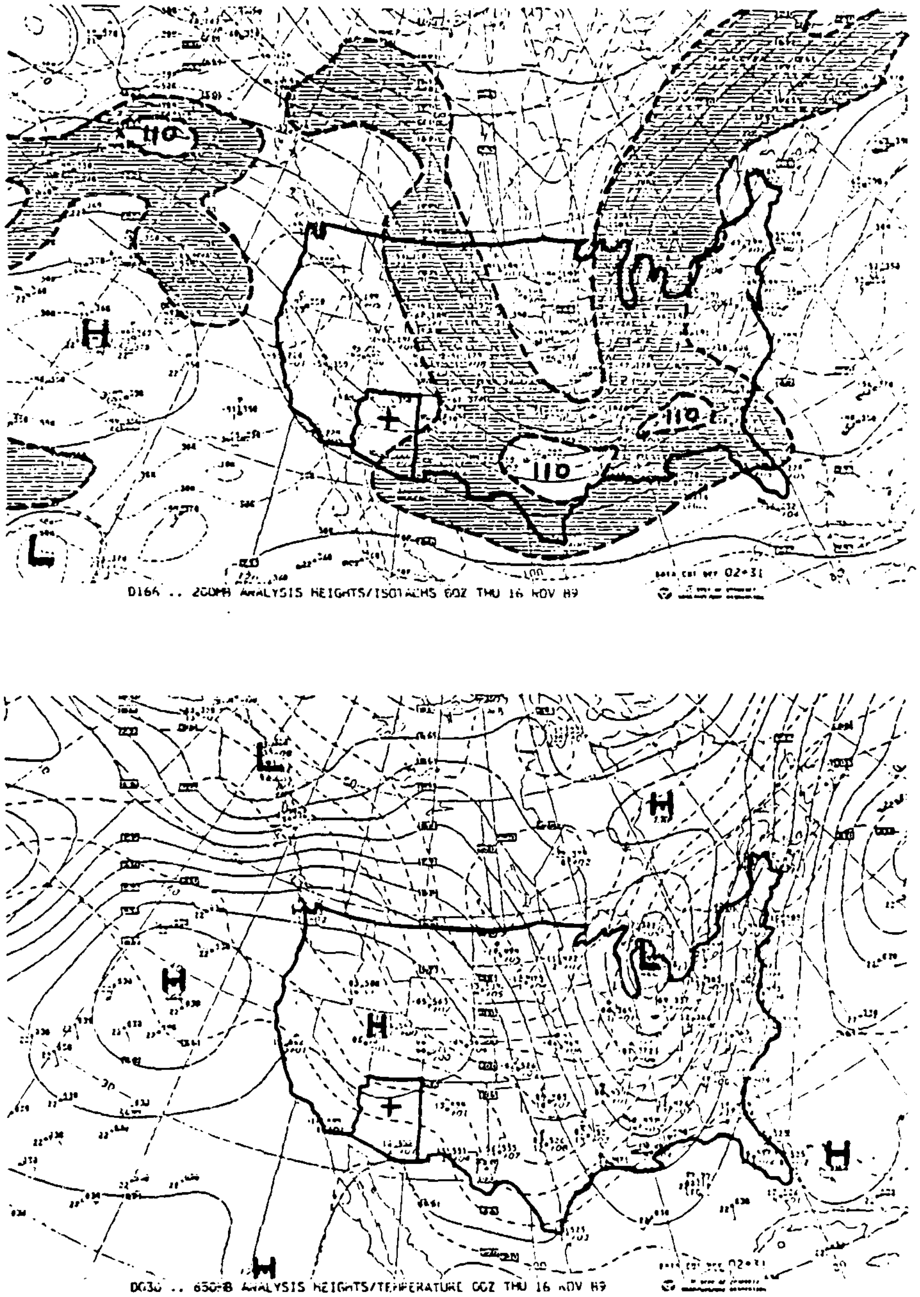


Fig 14. NWS 850 (bottom) and 200 (top) mb Charts: November 16, 0000 UTC

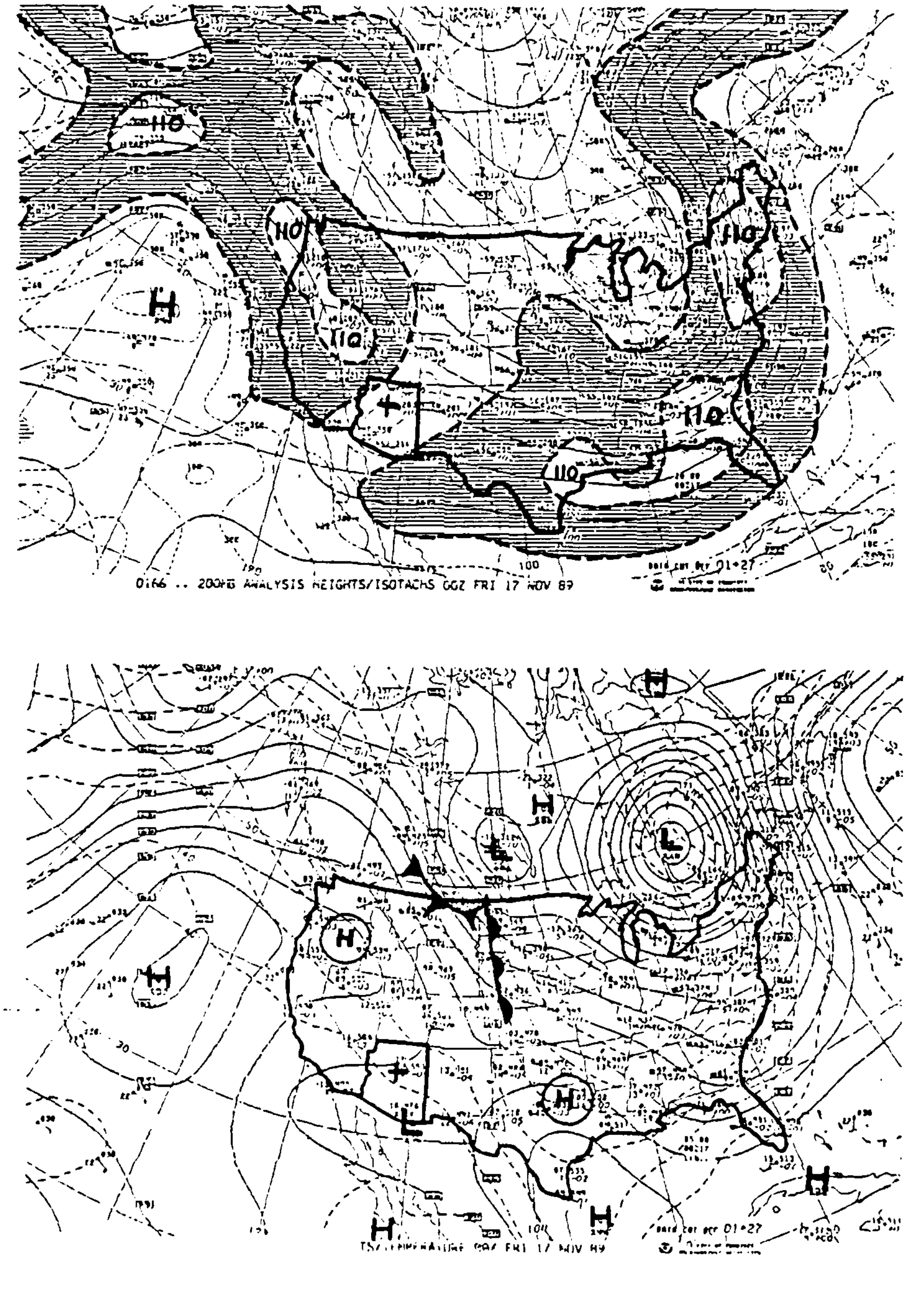
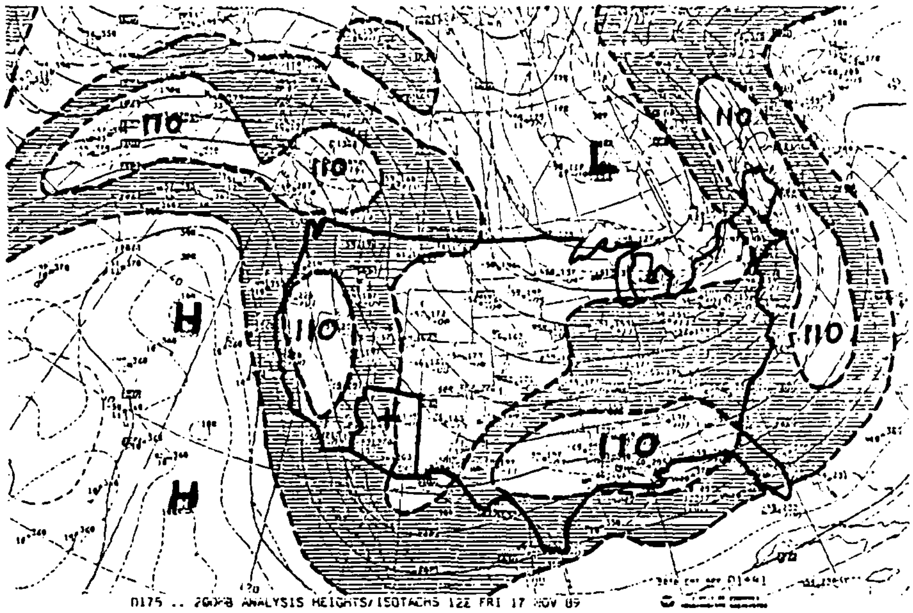


Fig 15. **NWS 850 (bottom) and 200 (top) mb Charts: November 17, 0000 UTC**



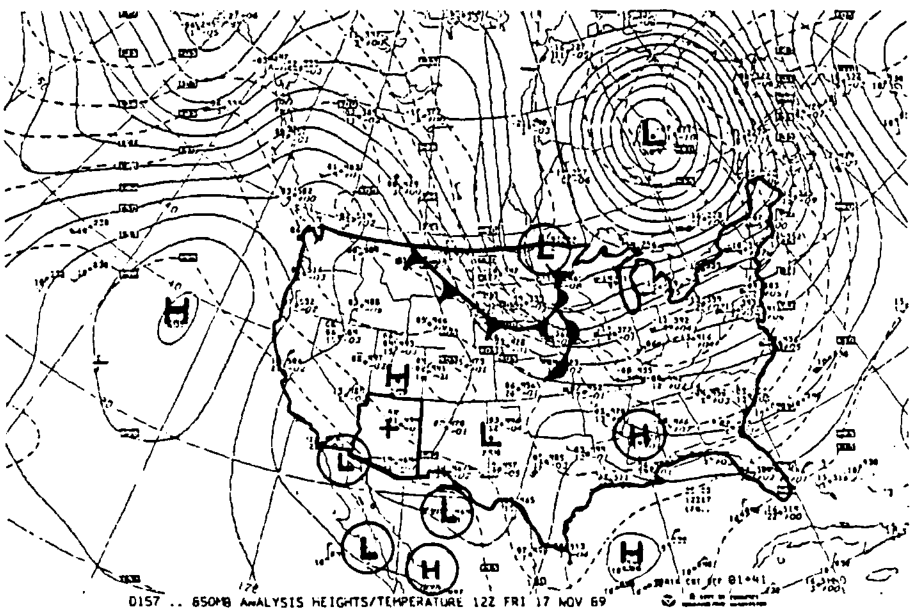
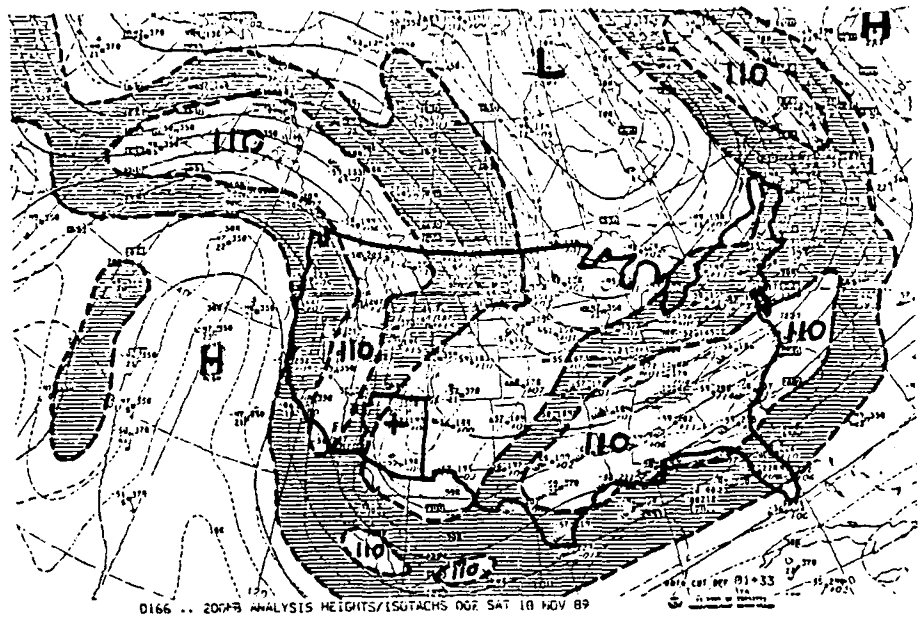


Fig 16. NWS 850 (bottom) and 200 (top) mb Charts: November 17, 1200 UTC



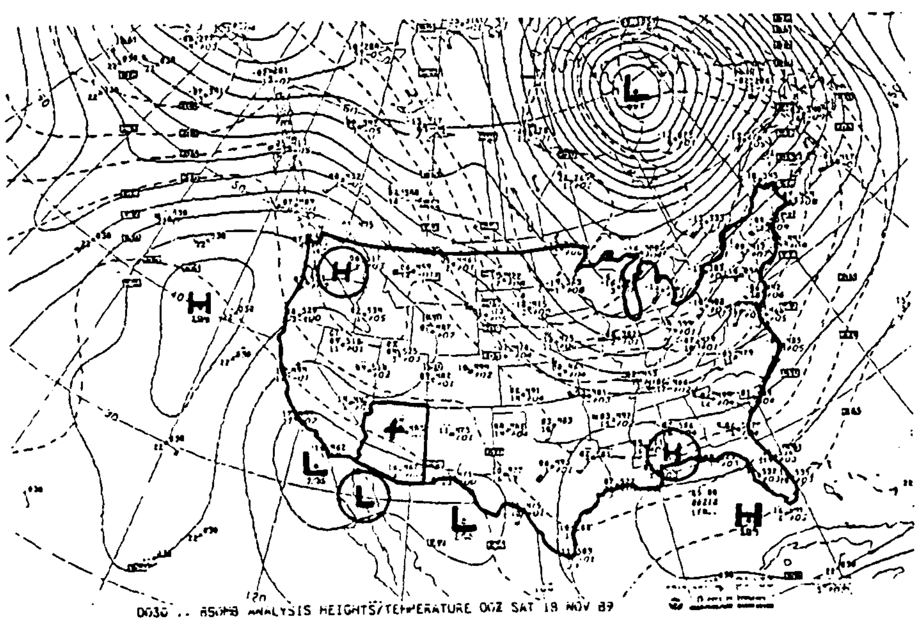


Fig 17. NWS 850 (bottom) and 200 (top) mb Charts: November 18, 0000 UTC

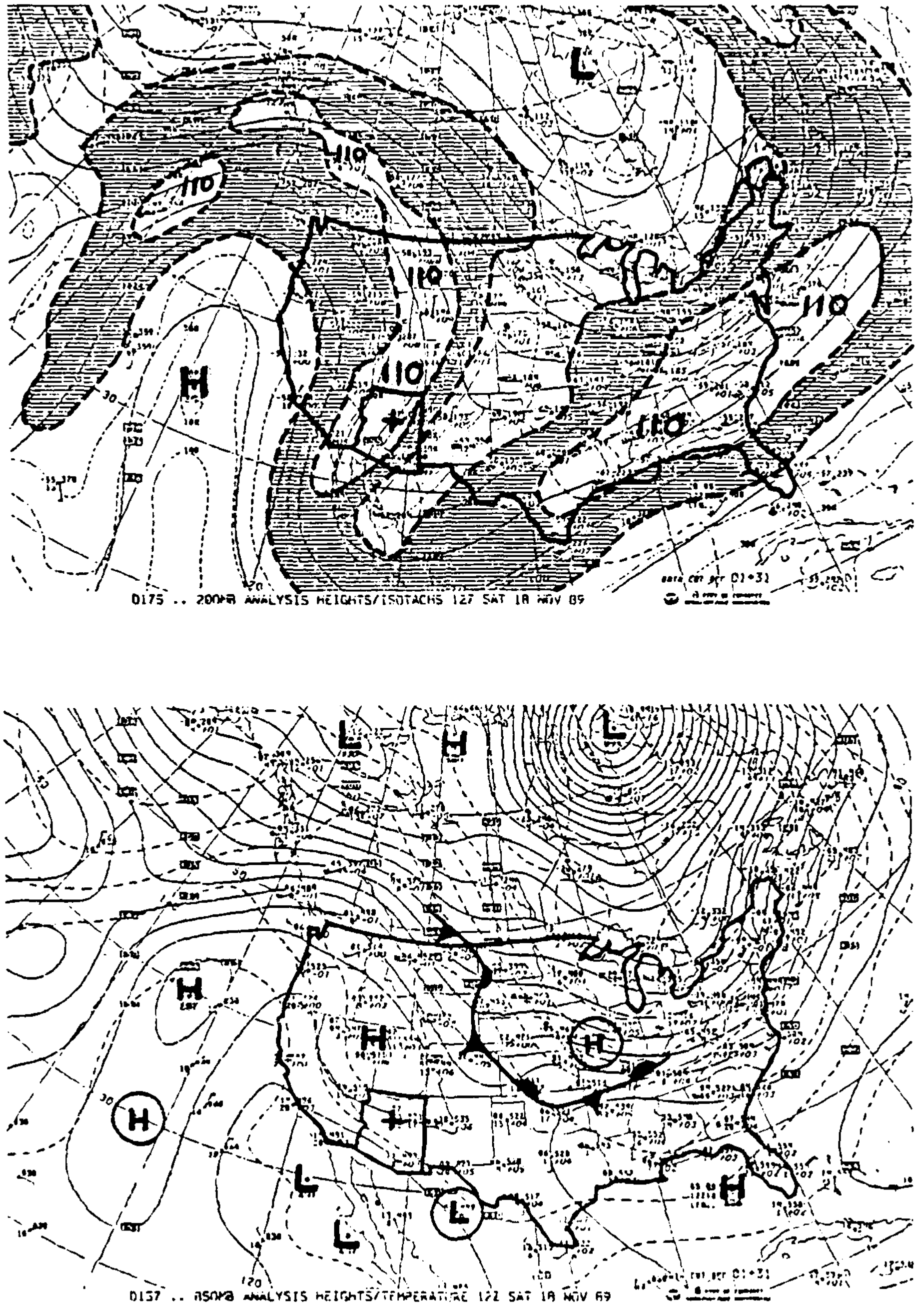


Fig 18. NWS 850 (bottom) and 200 (top) mb Charts: November 18, 1200 UTC

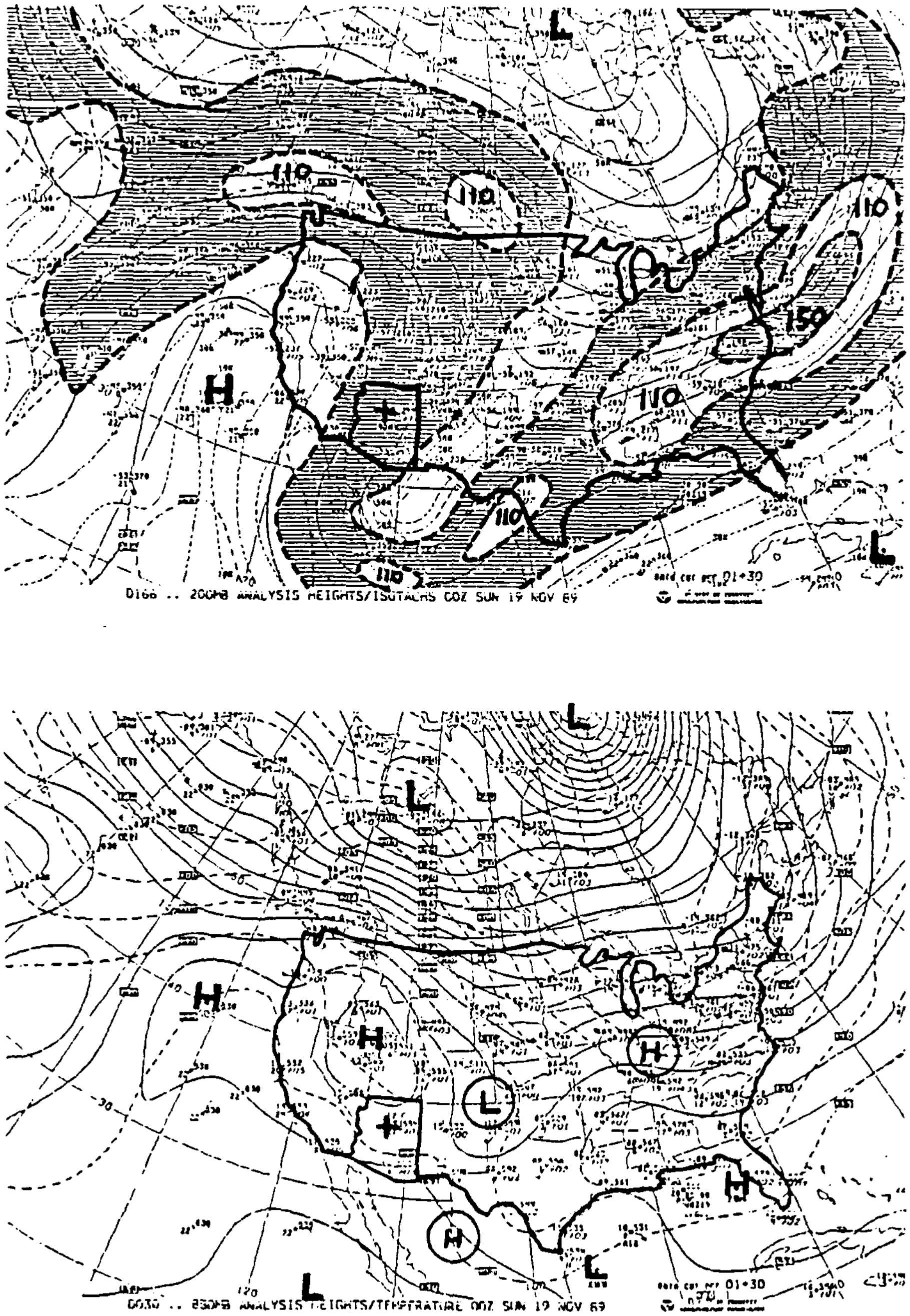


Fig 19. NWS 850 (bottom) and 200 (top) mb Charts: November 19, 0000 UTC

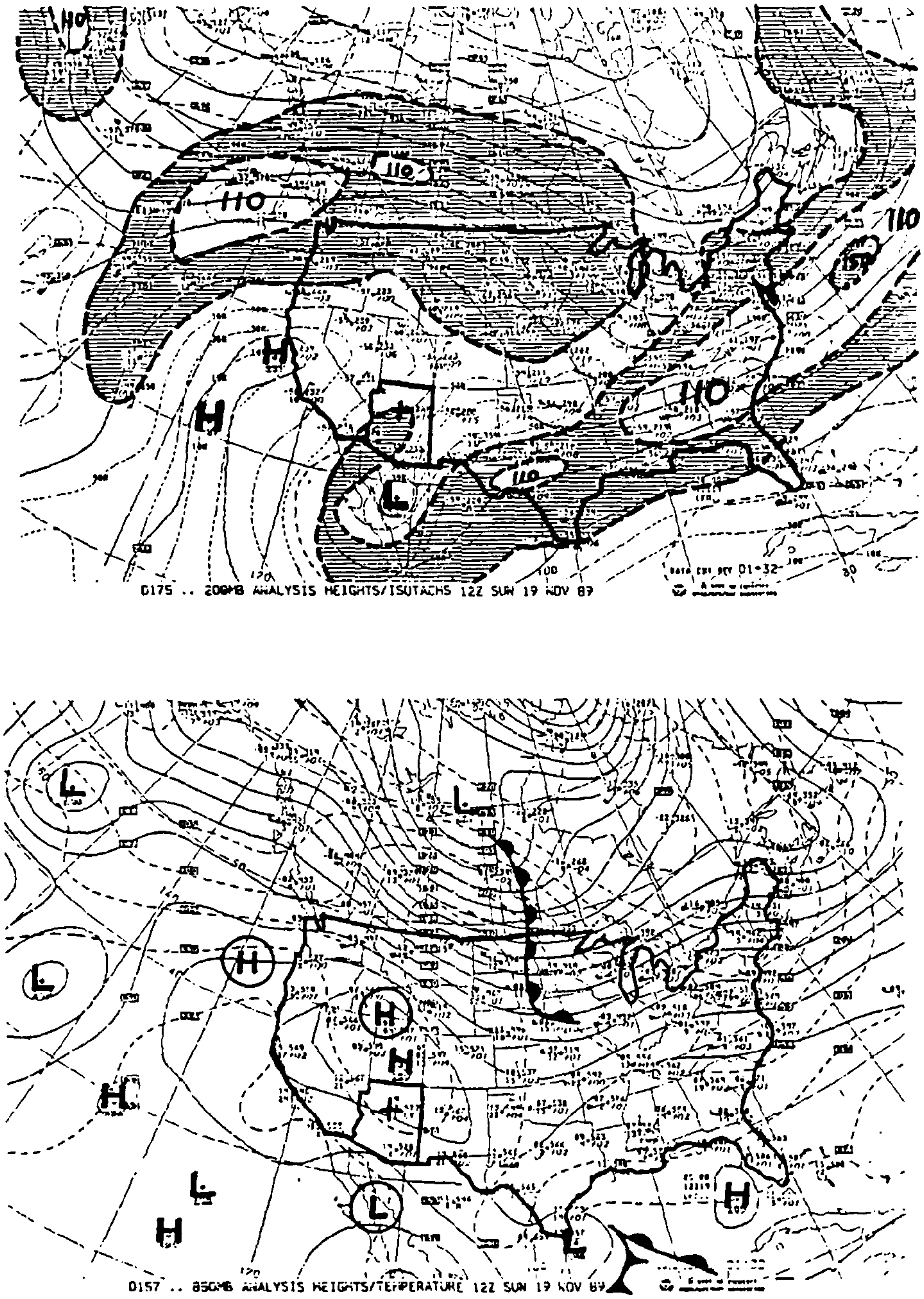
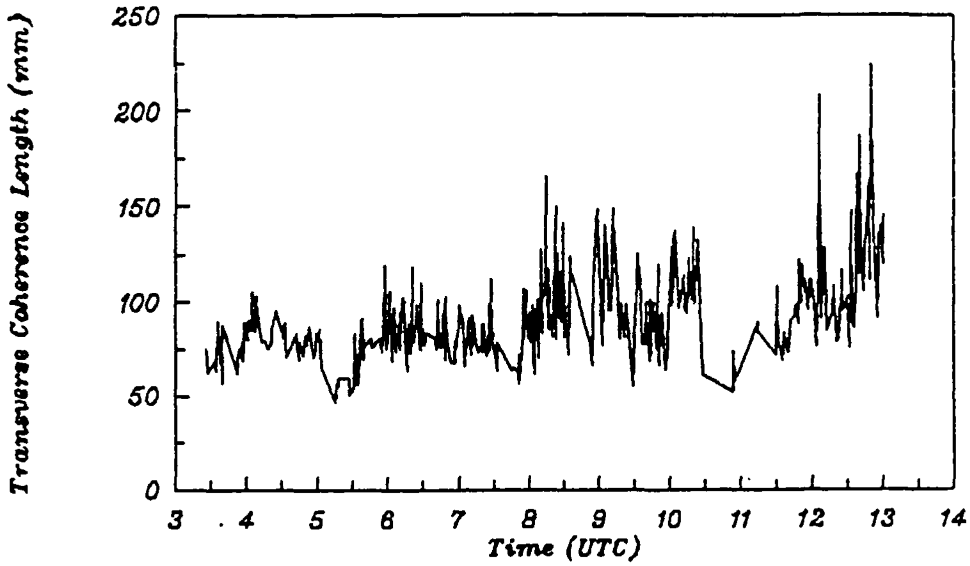


Fig 20. **NWS 850 (bottom) and 200 (top) mb Charts: November 19, 1200 UTC**

APPENDIX C. PROCESSED OPTICAL DATA (1989 November 13-19)

Appendix C displays nightly plots of all processed Transverse Coherence Length and Isoplanatic Angle data acquired between 13-19 November 1989.

ANDERSON MESA, AZ - 1989 NOVEMBER 13
Transverse Coherence Length



Isoplanatic Angle

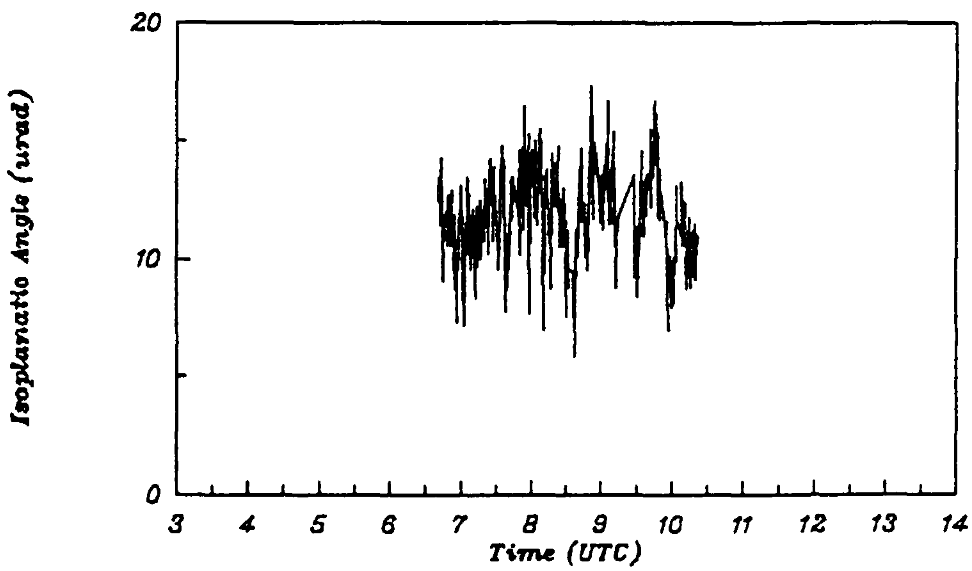
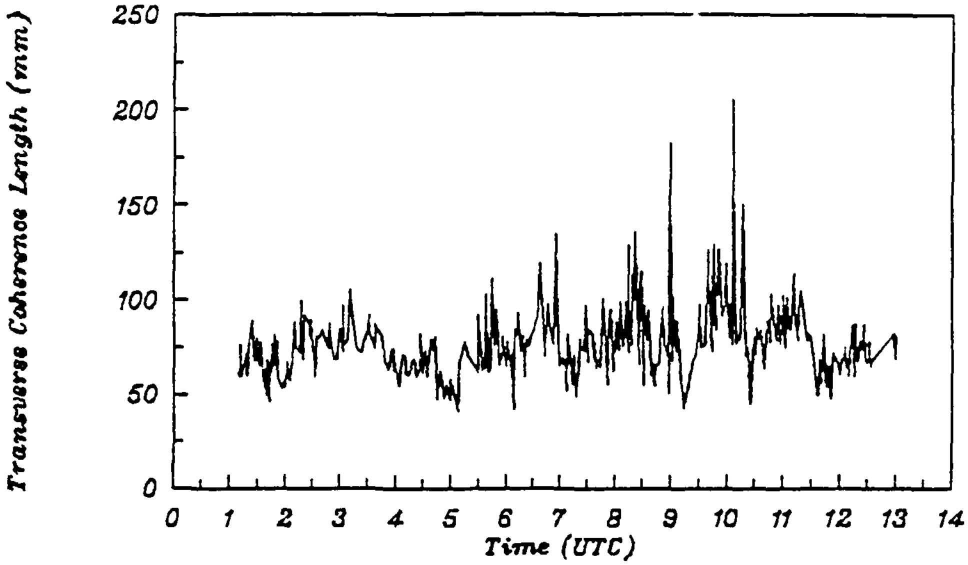


Fig 21. Anderson Mesa, Az Optical Data: 1989 November 13

ANDERSON MESA, AZ - 1989 NOVEMBER 14
Transverse Coherence Length



Isoplanatic Angle

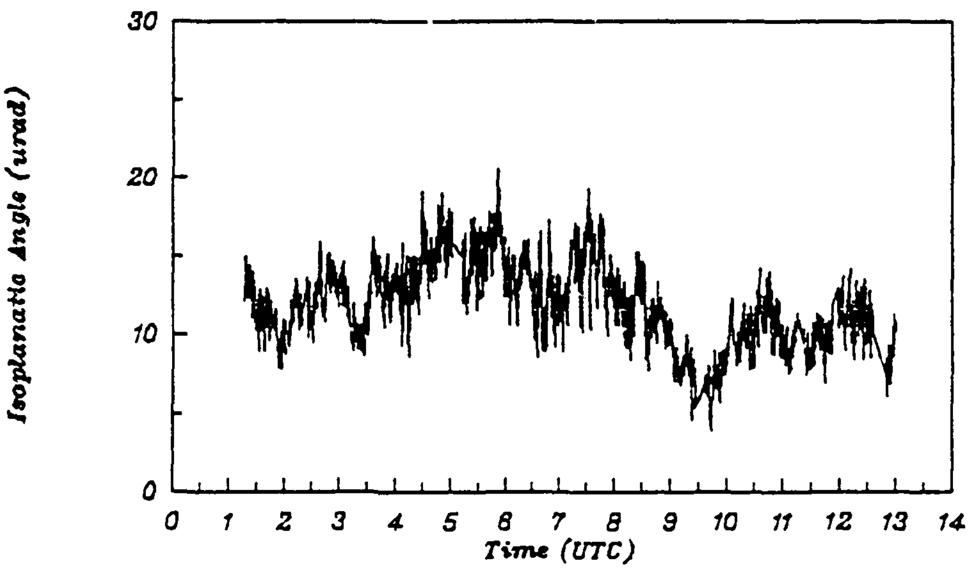
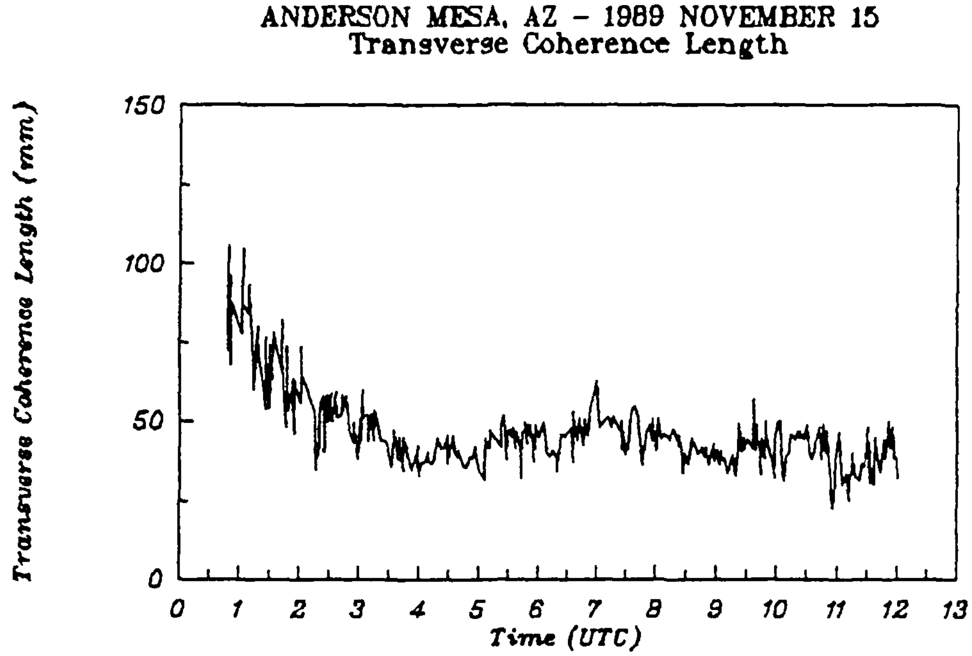


Fig 22. Anderson Mesa, Az Optical Data: 1989 November 14



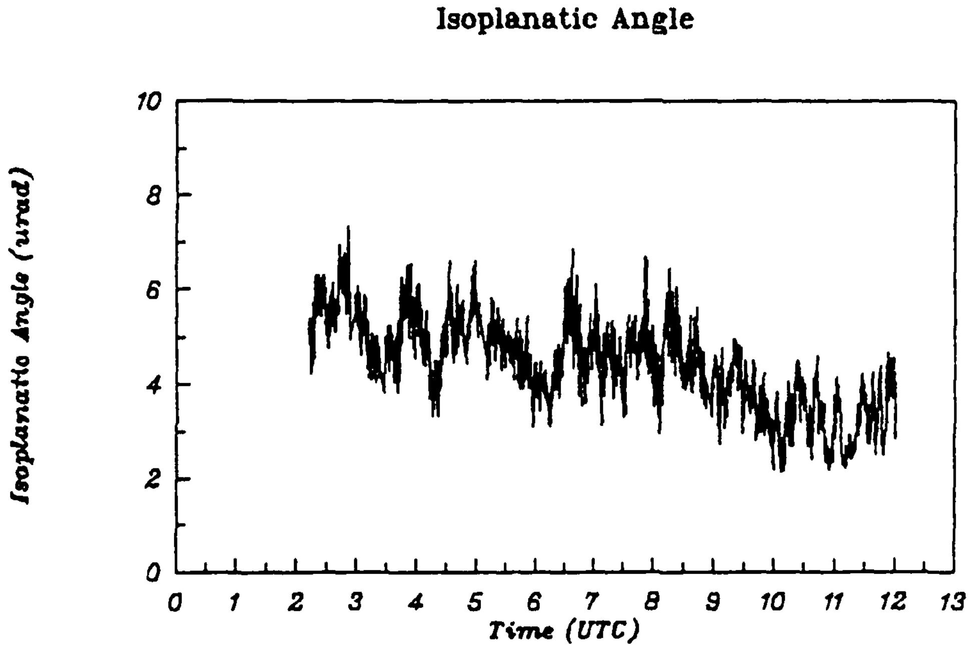
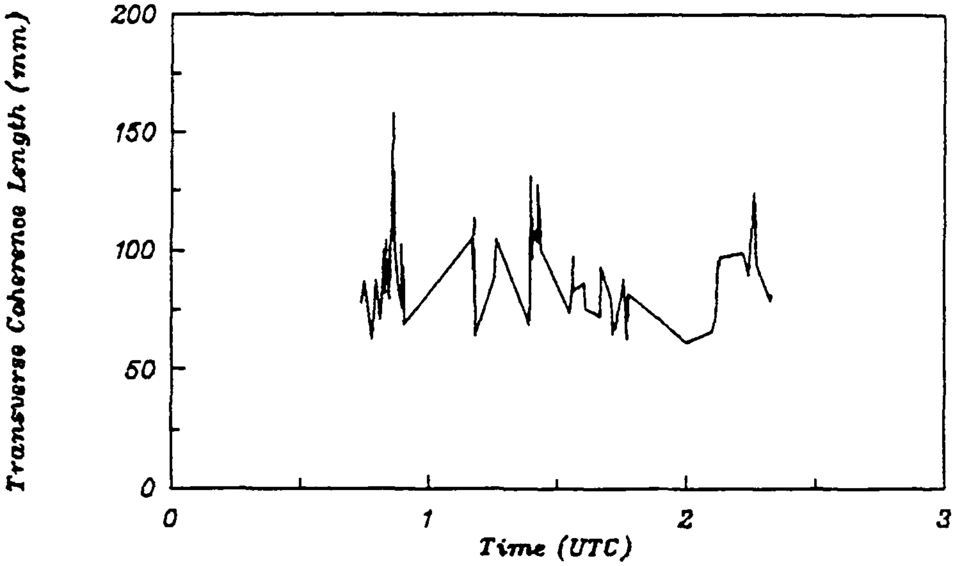


Fig 23. Anderson Mesa, Az Optical Data: 1989 November 15

ANDERSON MESA, AZ - 1989 NOVEMBER 16
Transverse Coherence Length



Isoplanatic Angle

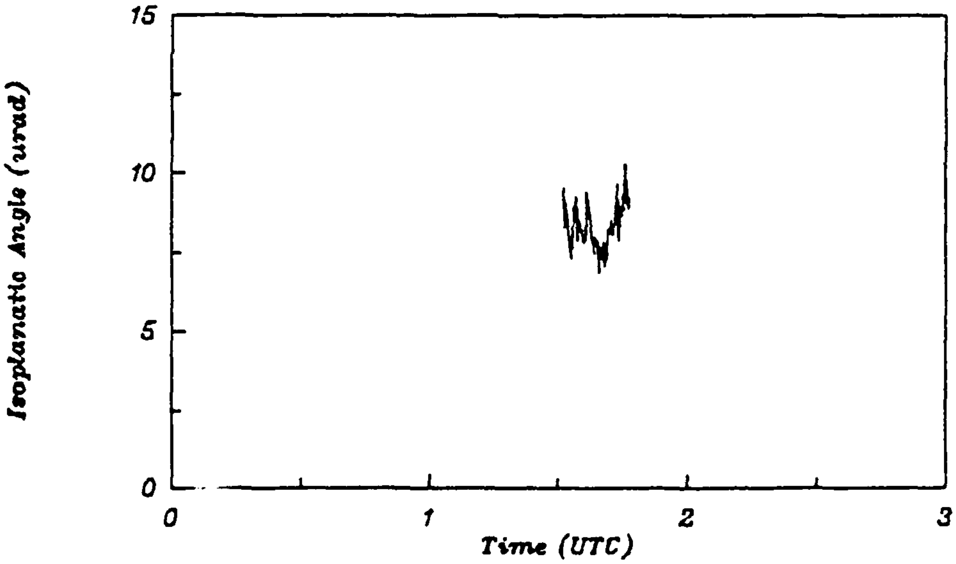
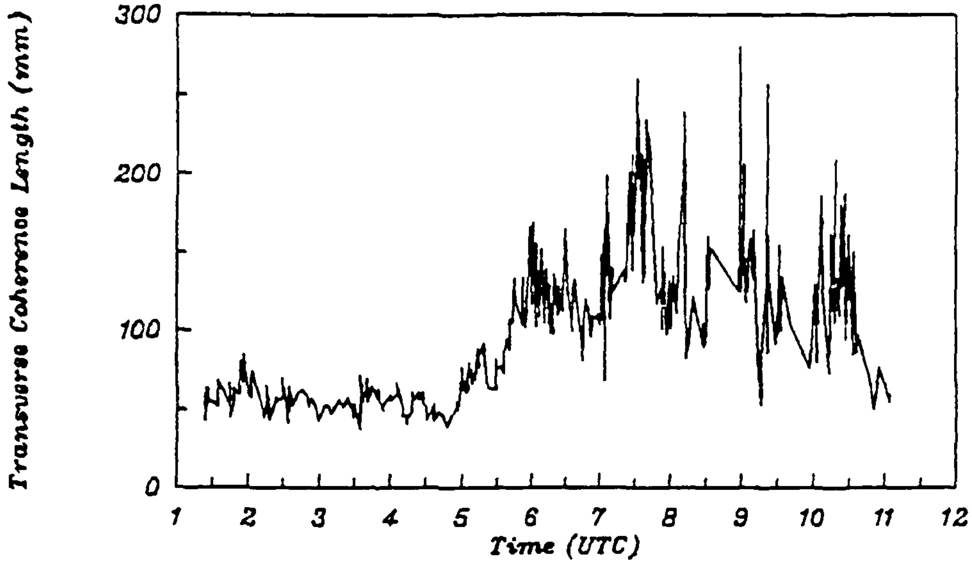


Fig 24. Anderson Mesa, Az Optical Data: 1989 November 16

ANDERSON MESA, AZ - 1989 NOVEMBER 17
Transverse Coherence Length



Isoplanatic Angle

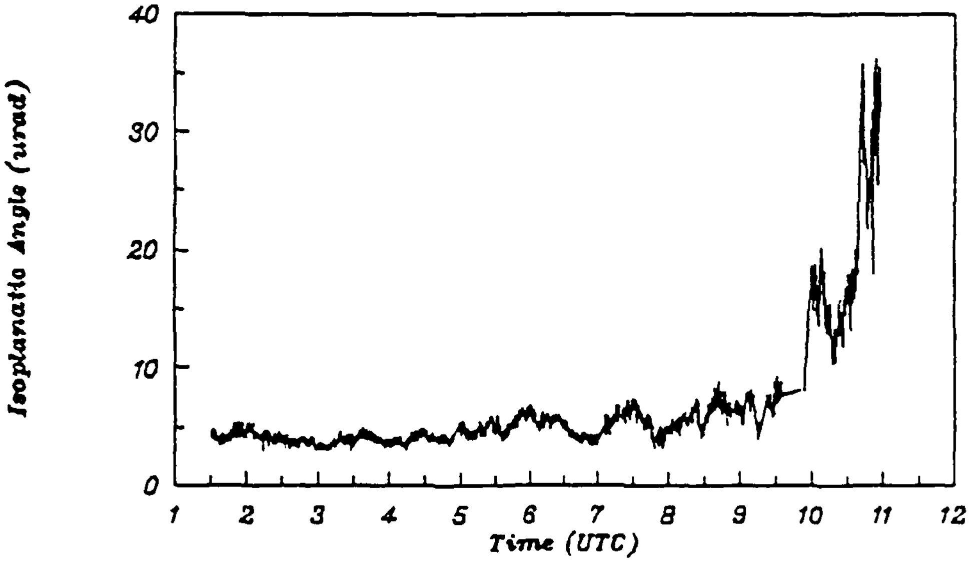


Fig 25. Anderson Mesa, Az Optical Data: 1989 November 17

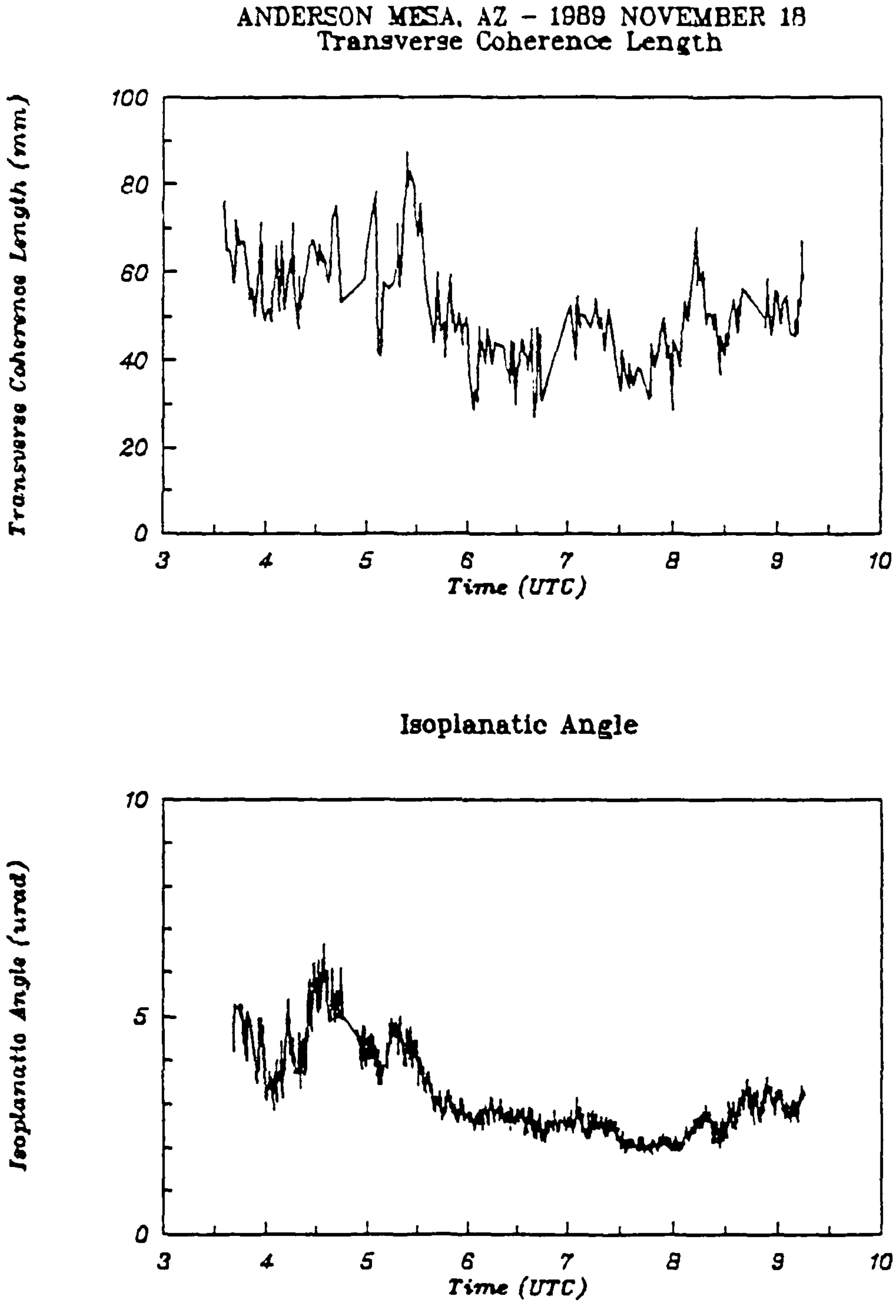
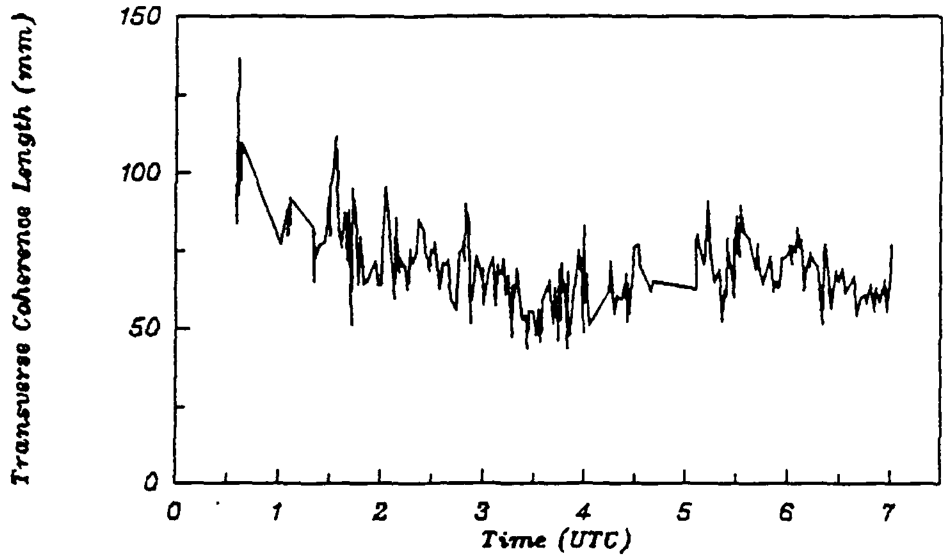


Fig 26. Anderson Mesa, Az Optical Data: 1989 November 18

ANDERSON MESA, AZ - 1989 NOVEMBER 19
Transverse Coherence Length



Isoplanatic Angle

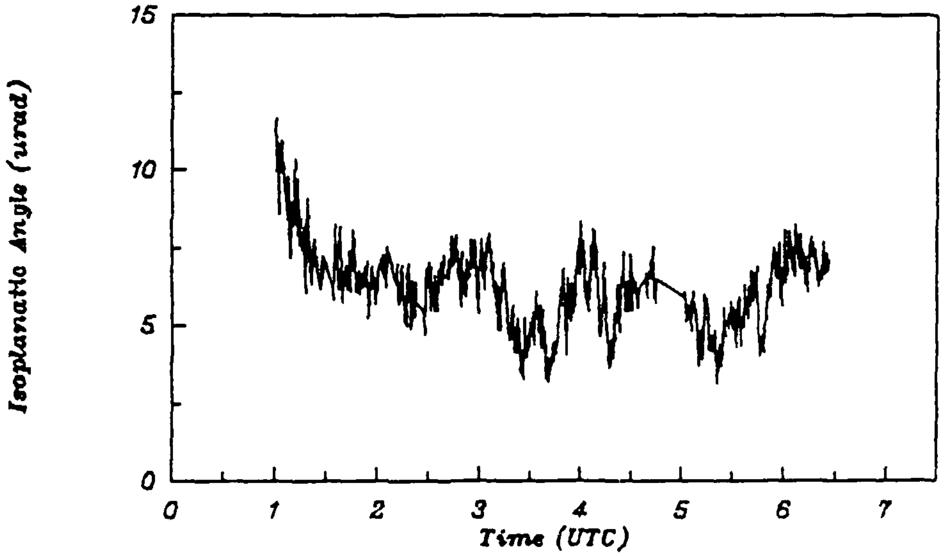


Fig 27. Anderson Mesa, Az Optical Data: 1989 November 19

APPENDIX D. TRANSVERSE COHERENCE LENGTH STATISTICS

Appendix D presents the transverse coherence length (r_o) un-normalized percent frequency distribution for each observing night (bin interval is 10 mm; optical wavelength is 500 nm). Empirical seeing quality histograms are also included. The bin intervals selected for this qualitative interpretation are a product of approximately 50 site surveys spanning 18-40 degrees latitude and 65-156 degrees longitude. The specific empirical seeing quality intervals are:

Empirical Seeing Quality	r_o measurement (mm)
Poor	00 - 50
Mediocre	51 - 100
Good	101 - 200
Very Good	201 - 300
Excellent	301 - 500

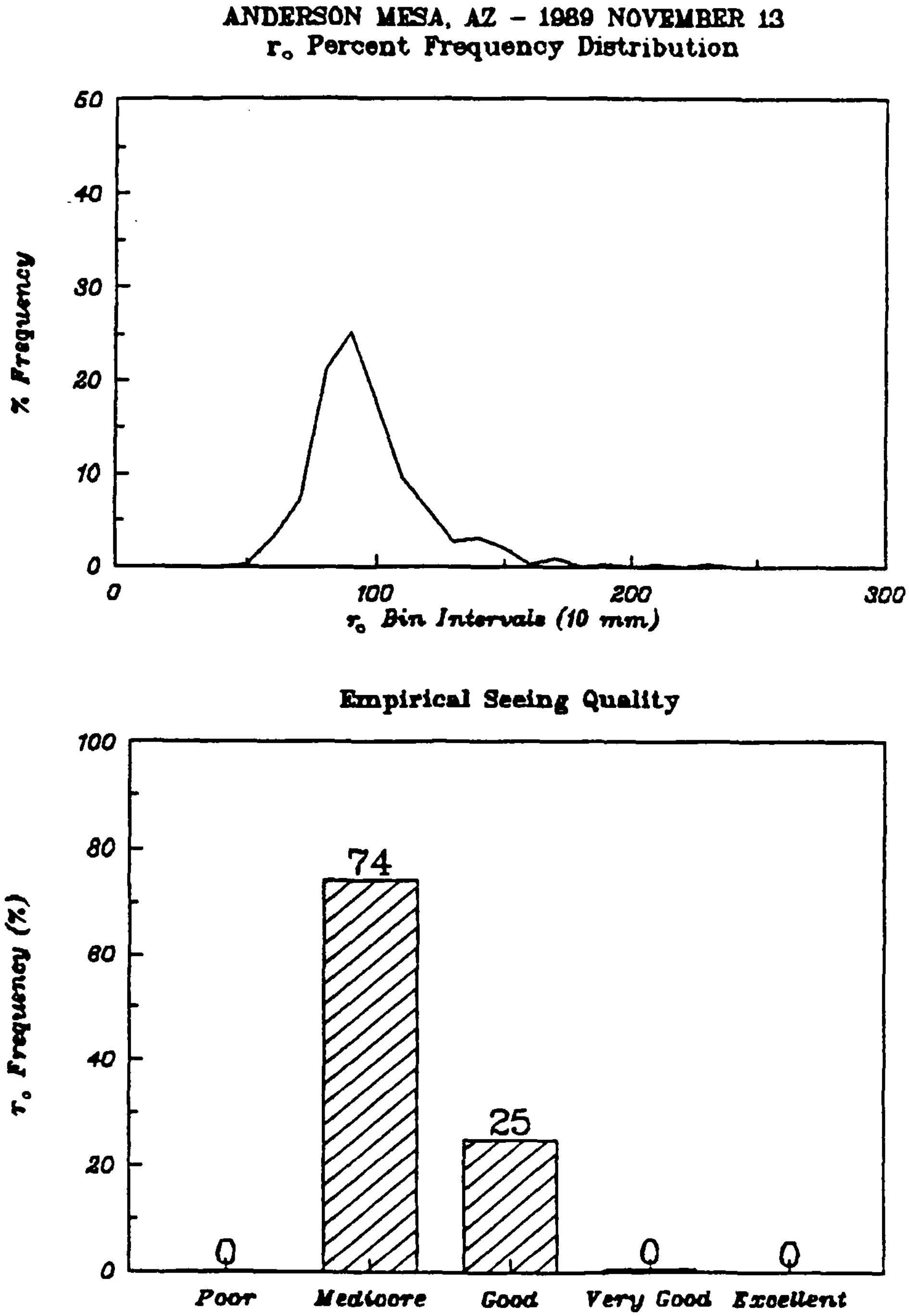


Fig 28. Anderson Mesa, Az r_o Statistics: 1989 Nov 13

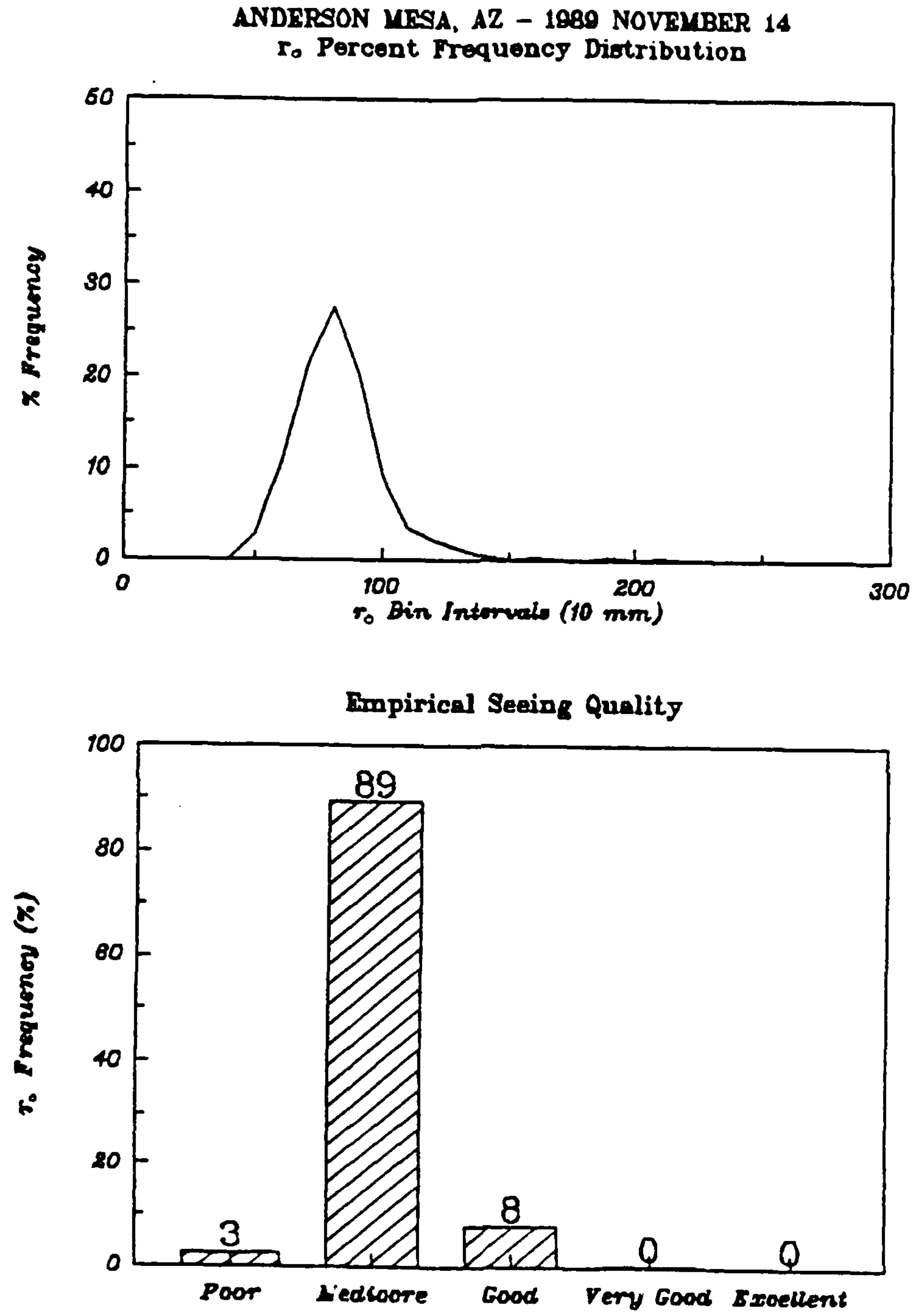
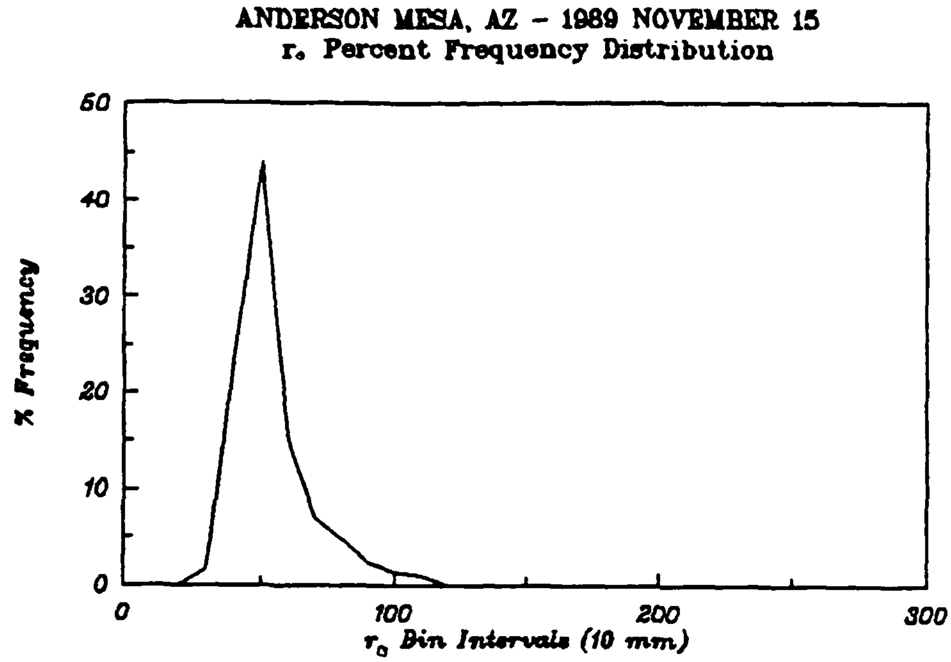


Fig 29. Anderson Mesa, Az r_o Statistics: 1989 Nov 14



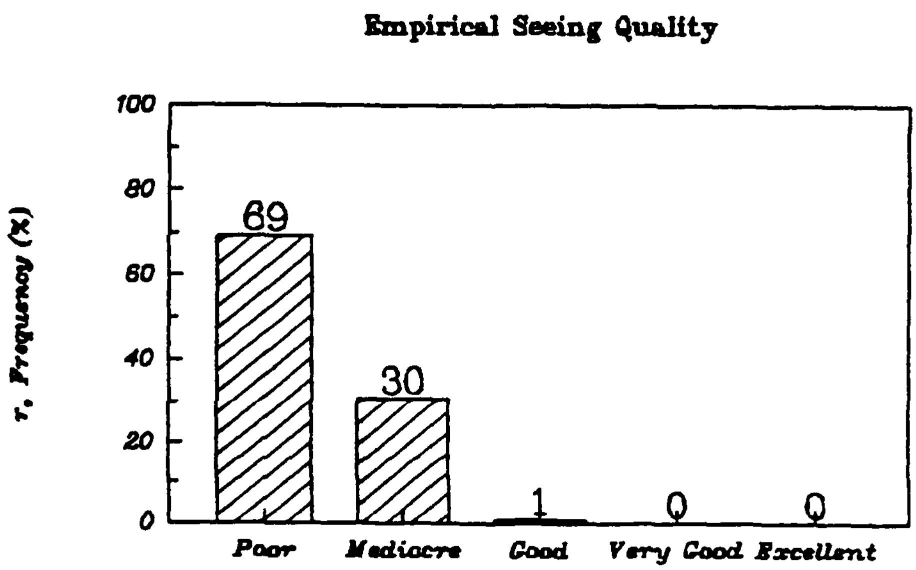


Fig 30. Anderson Mesa, Az r_o Statistics: 1989 Nov 15

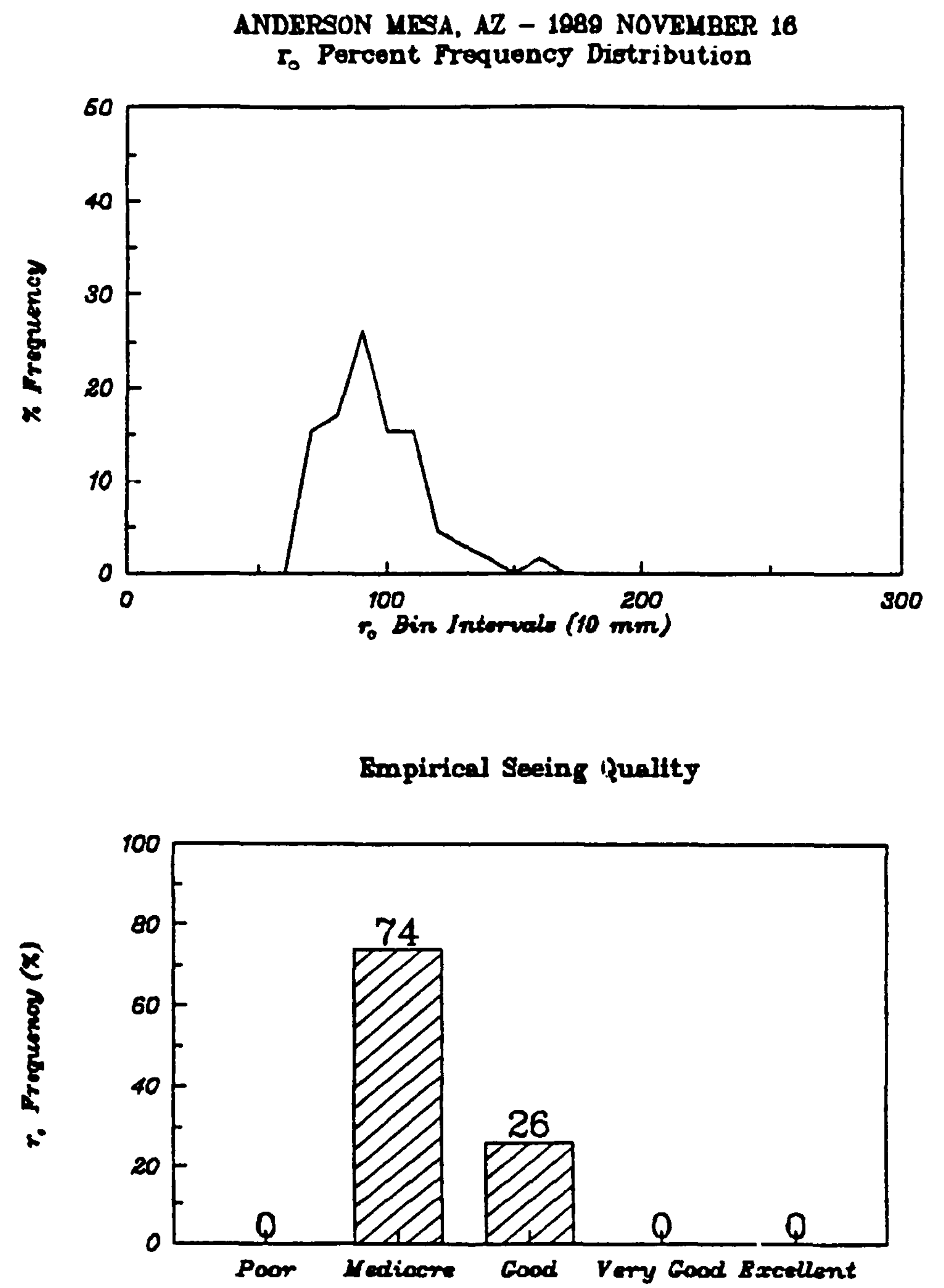
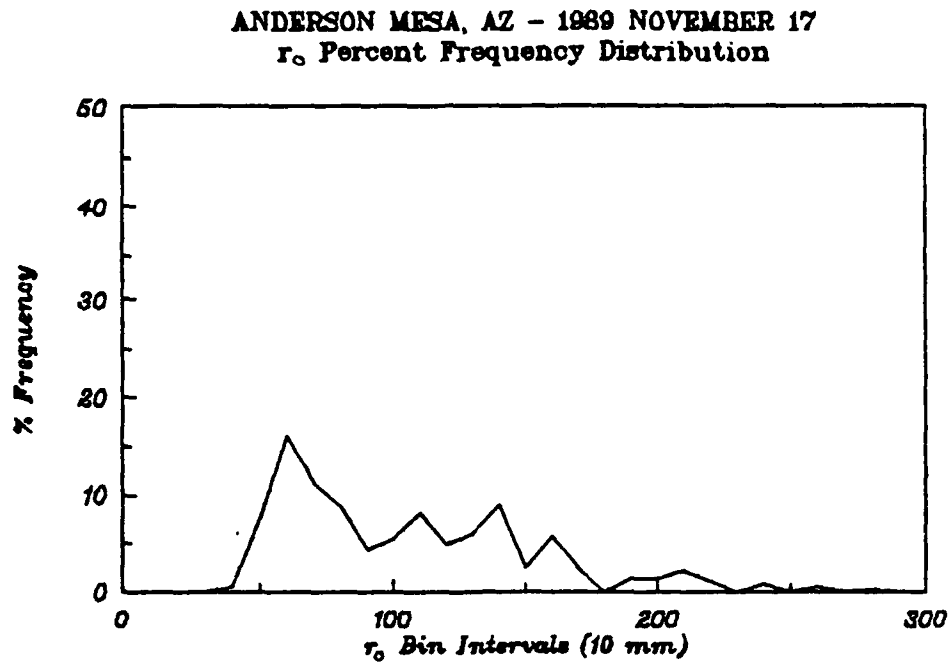


Fig 31. Anderson Mesa, Az r_o Statistics: 1989 Nov 16



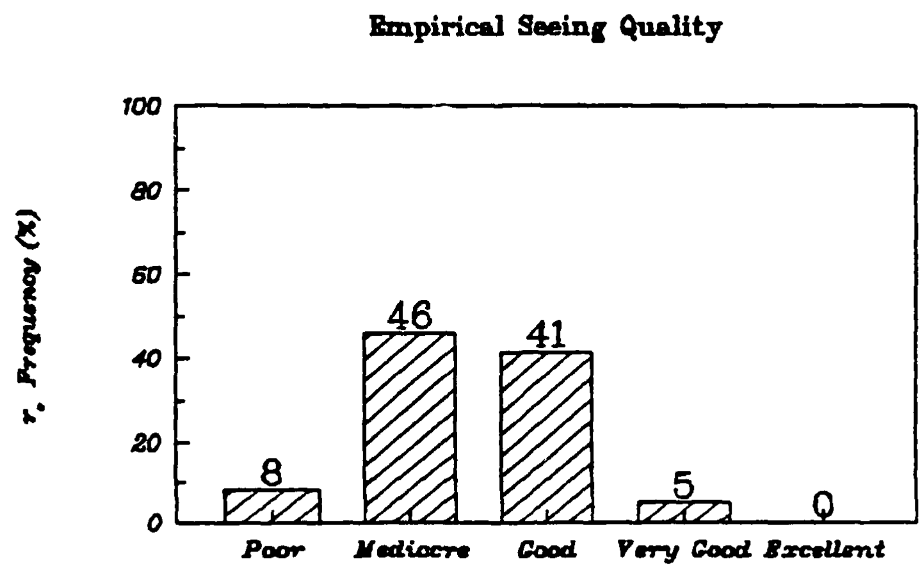
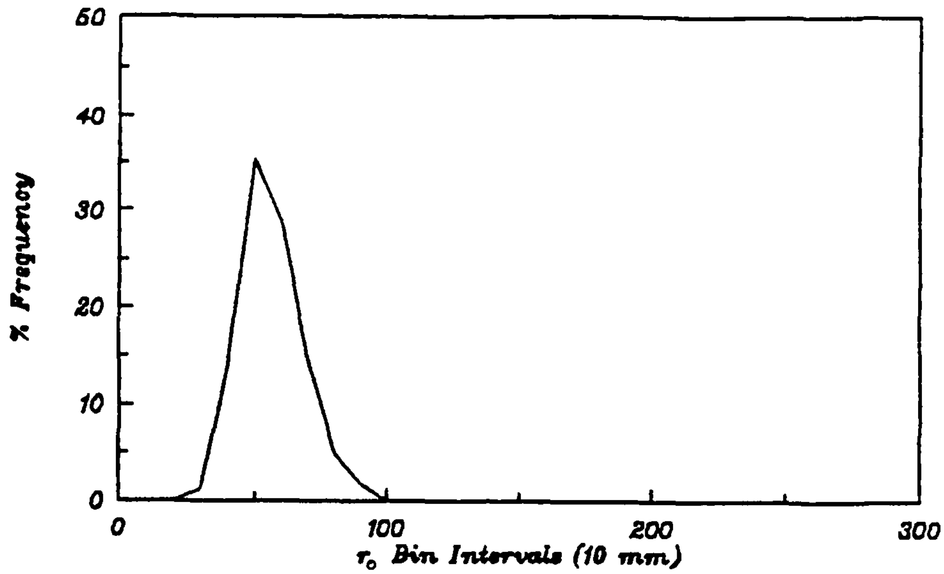


Fig 32. Anderson Mesa, Az r_o Statistics: 1989 Nov 17

ANDERSON MESA, AZ - 1989 NOVEMBER 18
r_o Percent Frequency Distribution



Empirical Seeing Quality

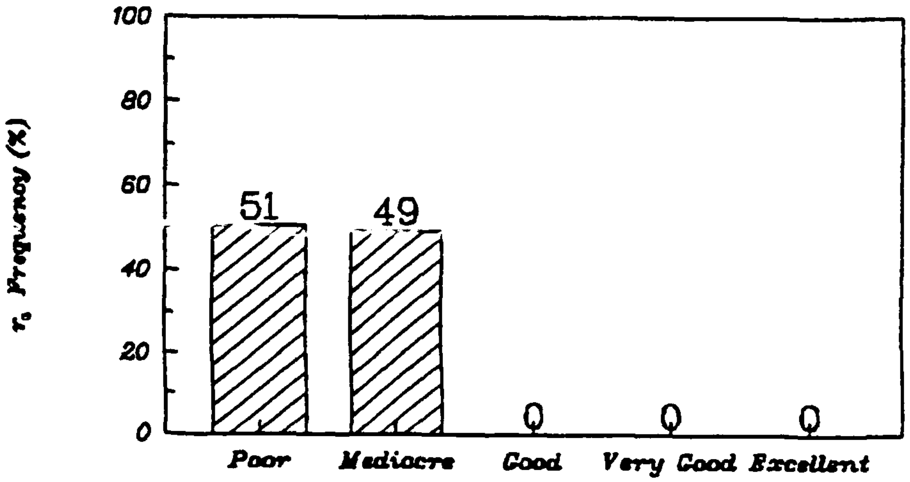


Fig 33. Anderson Mesa, Az r_o Statistics: 1989 Nov 18

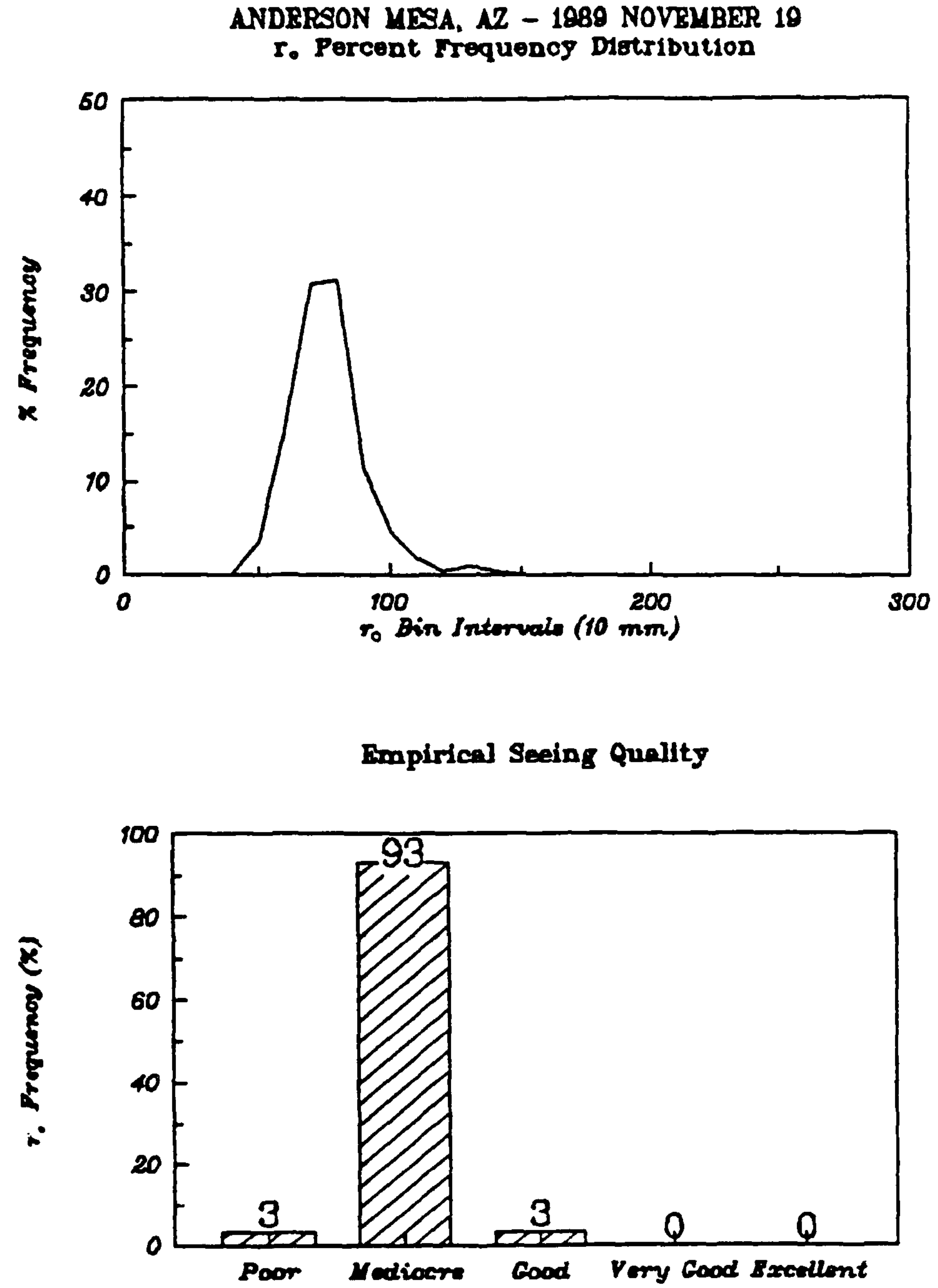


Fig 34. Anderson Mesa, Az r_o Statistics: 1989 Nov 19

APPENDIX E. ISOPLANATIC ANGLE STATISTICS

To assist with the interpretation of the isoplanatic angle (θ_o) measurements, an un-normalized frequency distribution and an empirical seeing quality plot for each sampling session have been provided in Appendix E. The bin-size for this frequency distribution is 1 urad. The empirical seeing quality graphs use the following bin intervals:

Empirical Seeing Quality	θ_o measurement (urad)
Very Poor	0 - 4.0
Poor	4.1 - 8.0
Mediocre	8.1 - 12.0
Good	12.1 - 20.0
Very Good	20.1 - 30.0
Excellent	30.1 - 50.0

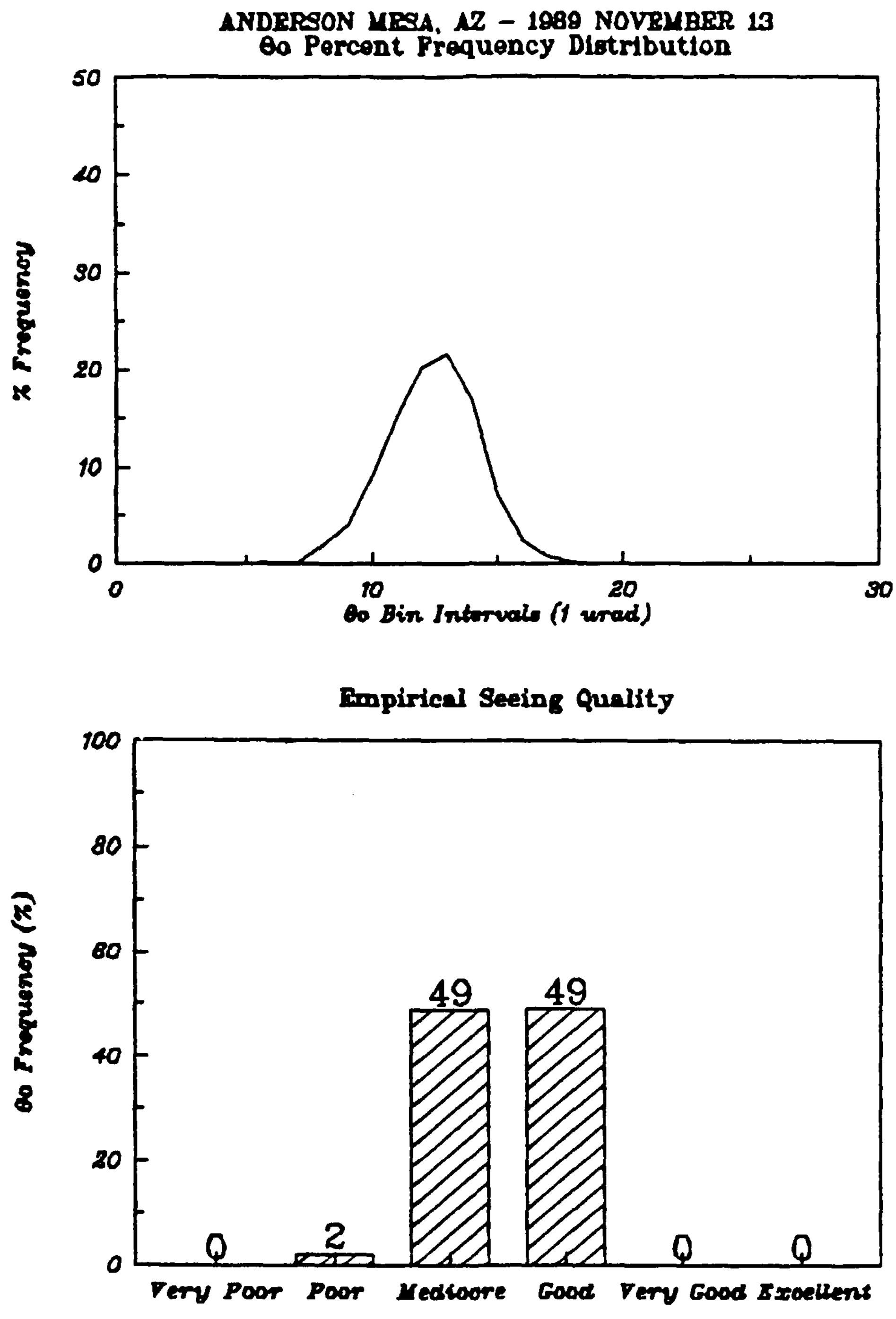


Fig 35. Anderson Mesa, Az θ_o Statistics: 1989 Nov 13

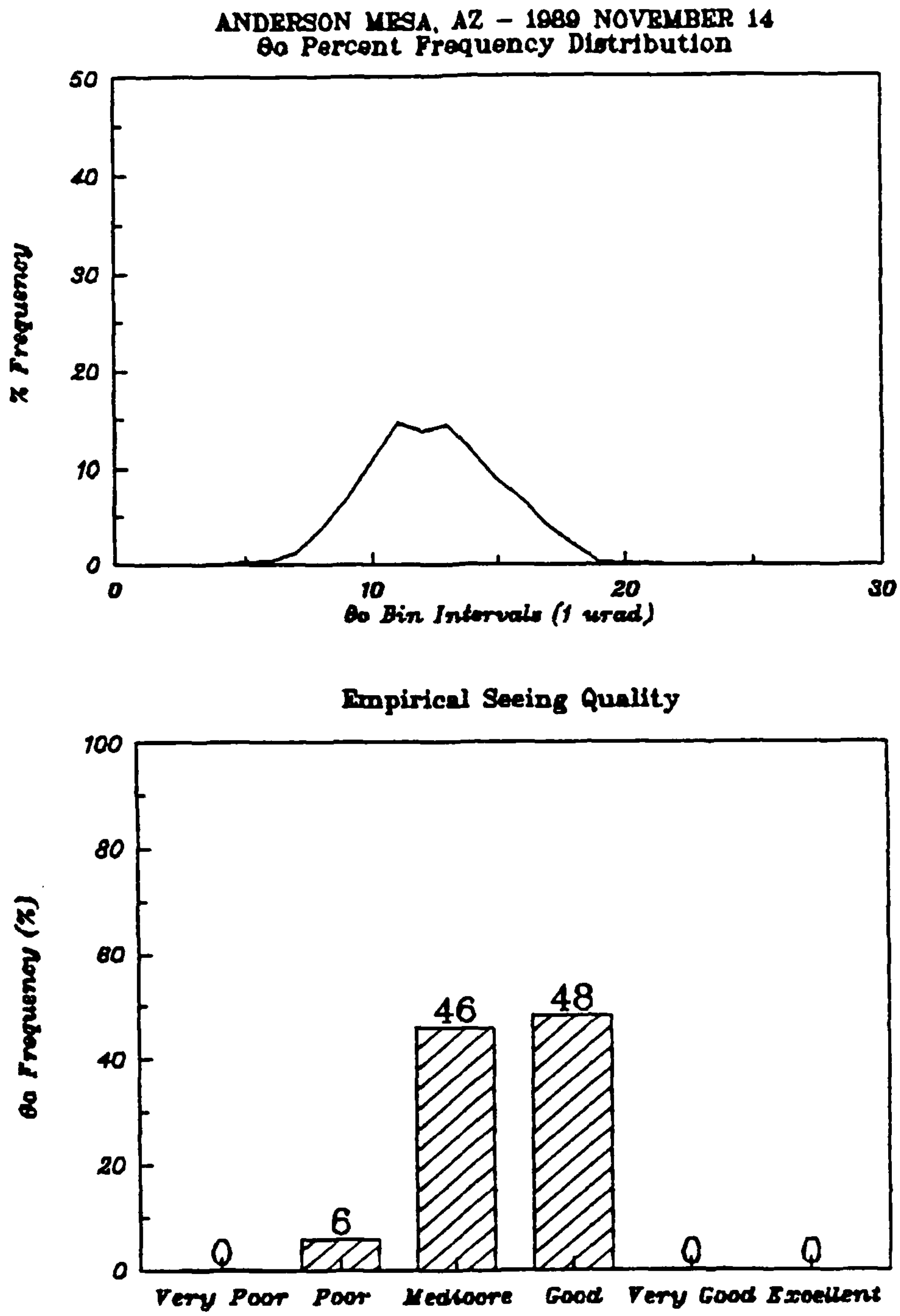


Fig 36. Anderson Mesa, Az θ_o Statistics: 1989 Nov 14

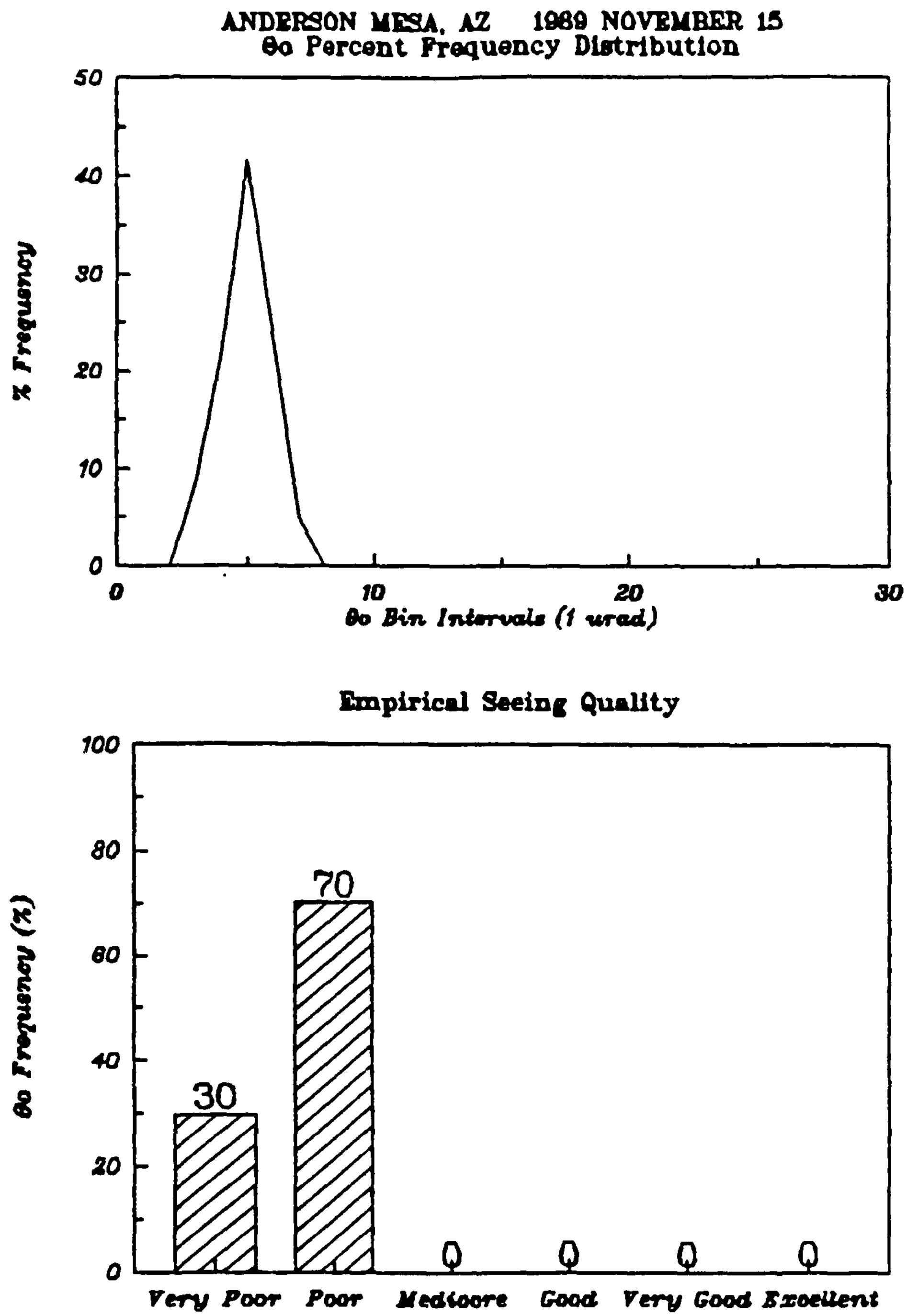


Fig 37. Anderson Mesa, Az θ_o Statistics: 1989 Nov 15

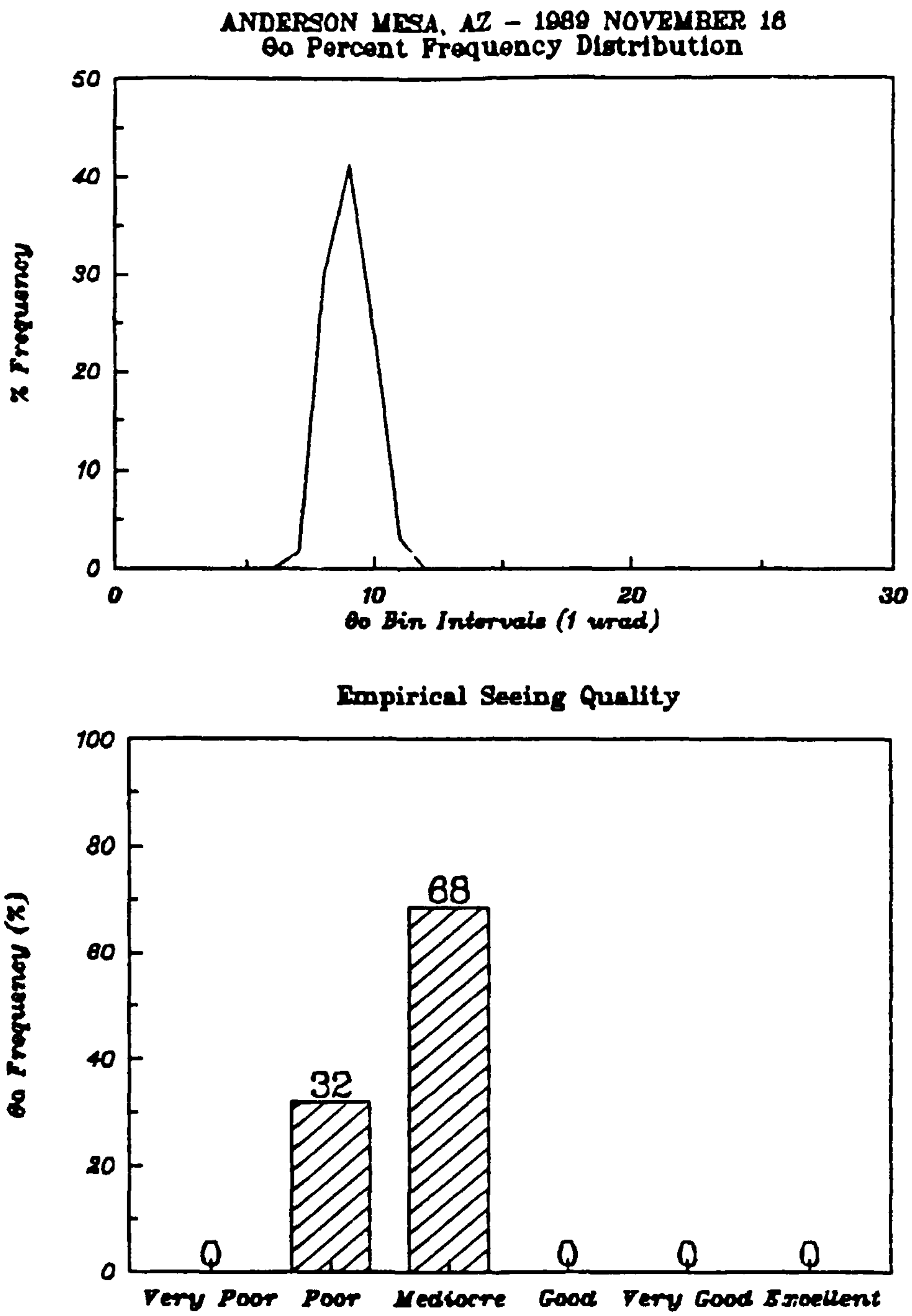


Fig 38. Anderson Mesa, Az θ_o Statistics: 1989 Nov 16

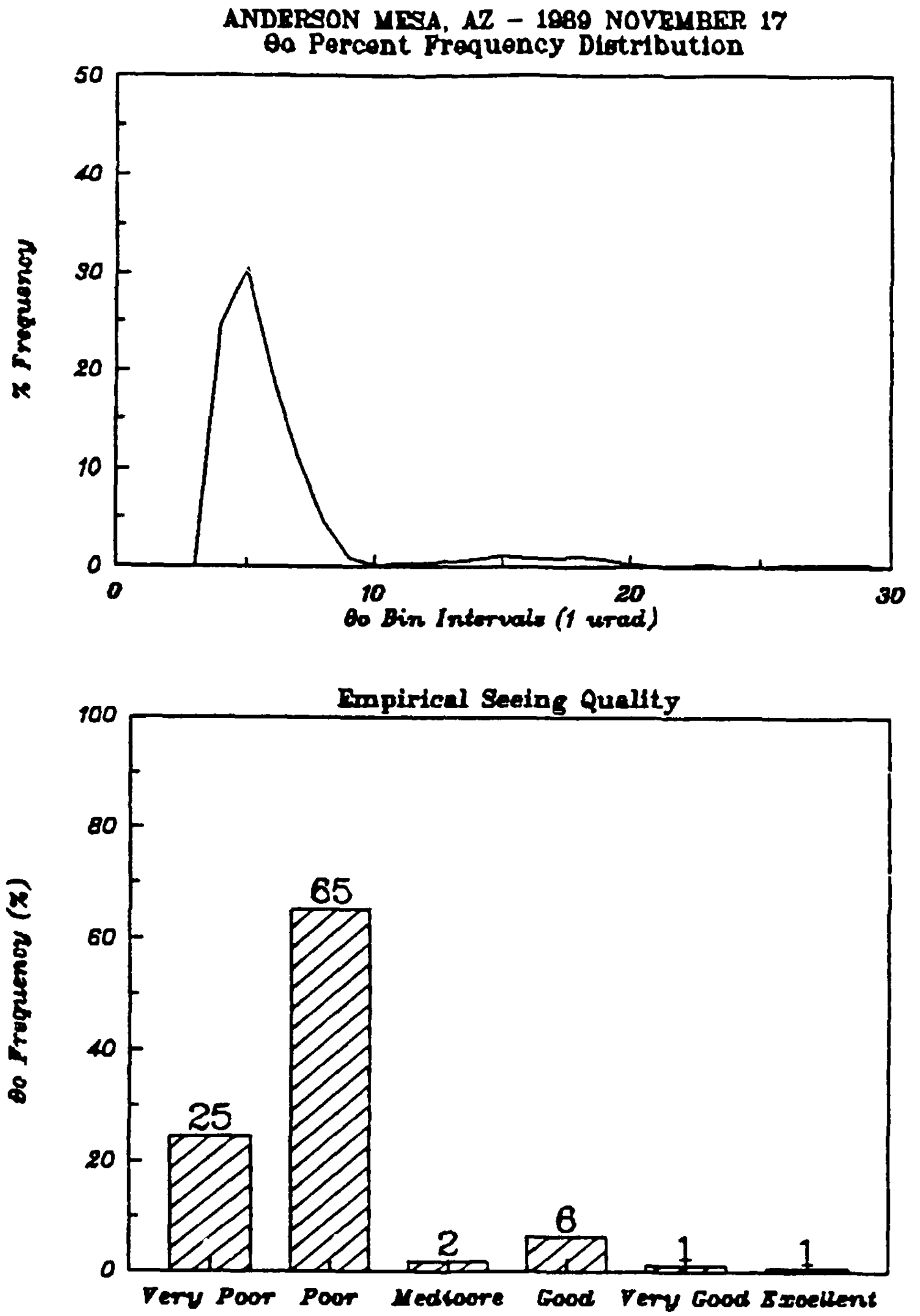


Fig 39. Anderson Mesa, Az θ_o Statistics: 1989 Nov 17

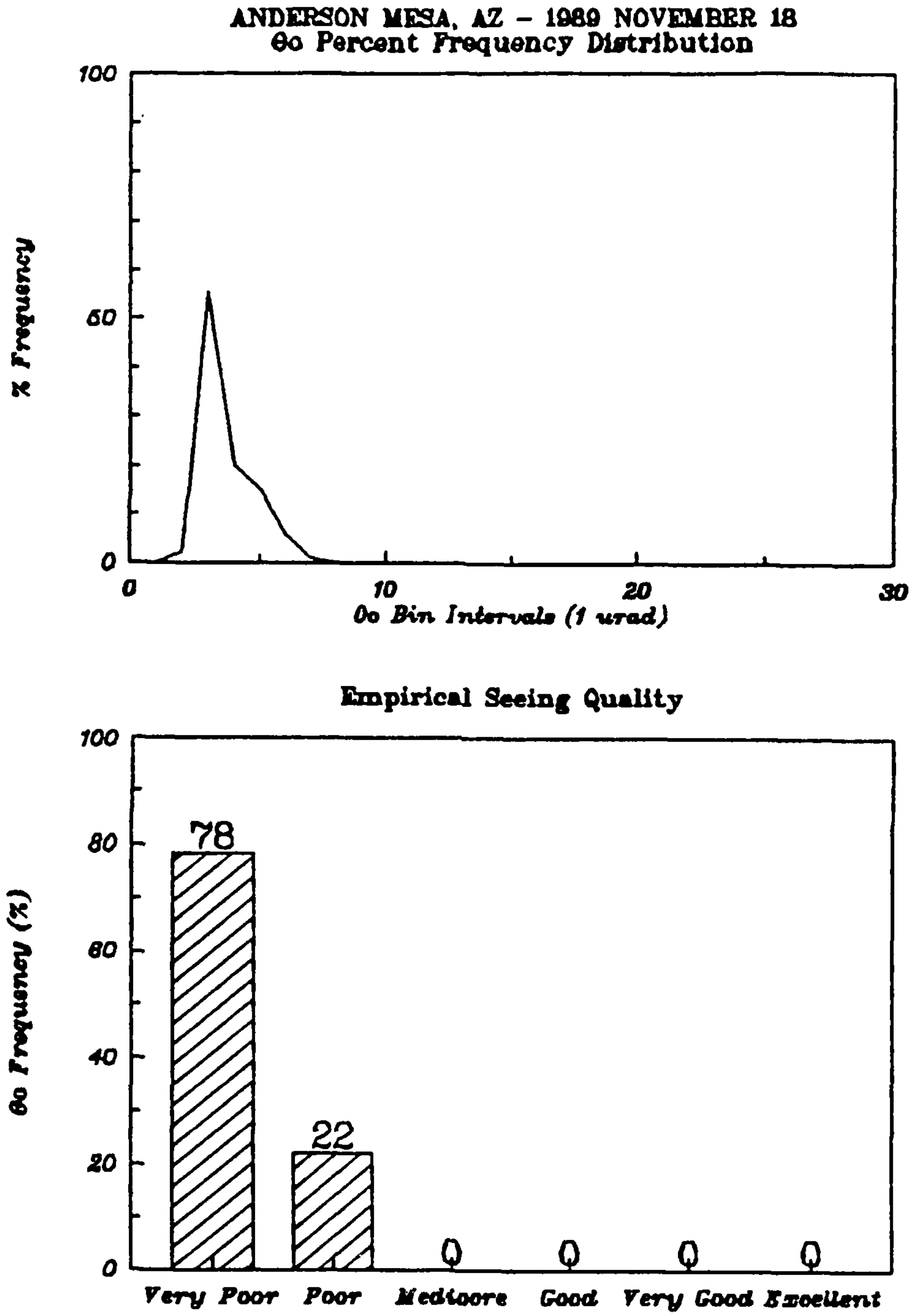


Fig 40. Anderson Mesa, Az θ_o Statistics: 1989 Nov 18

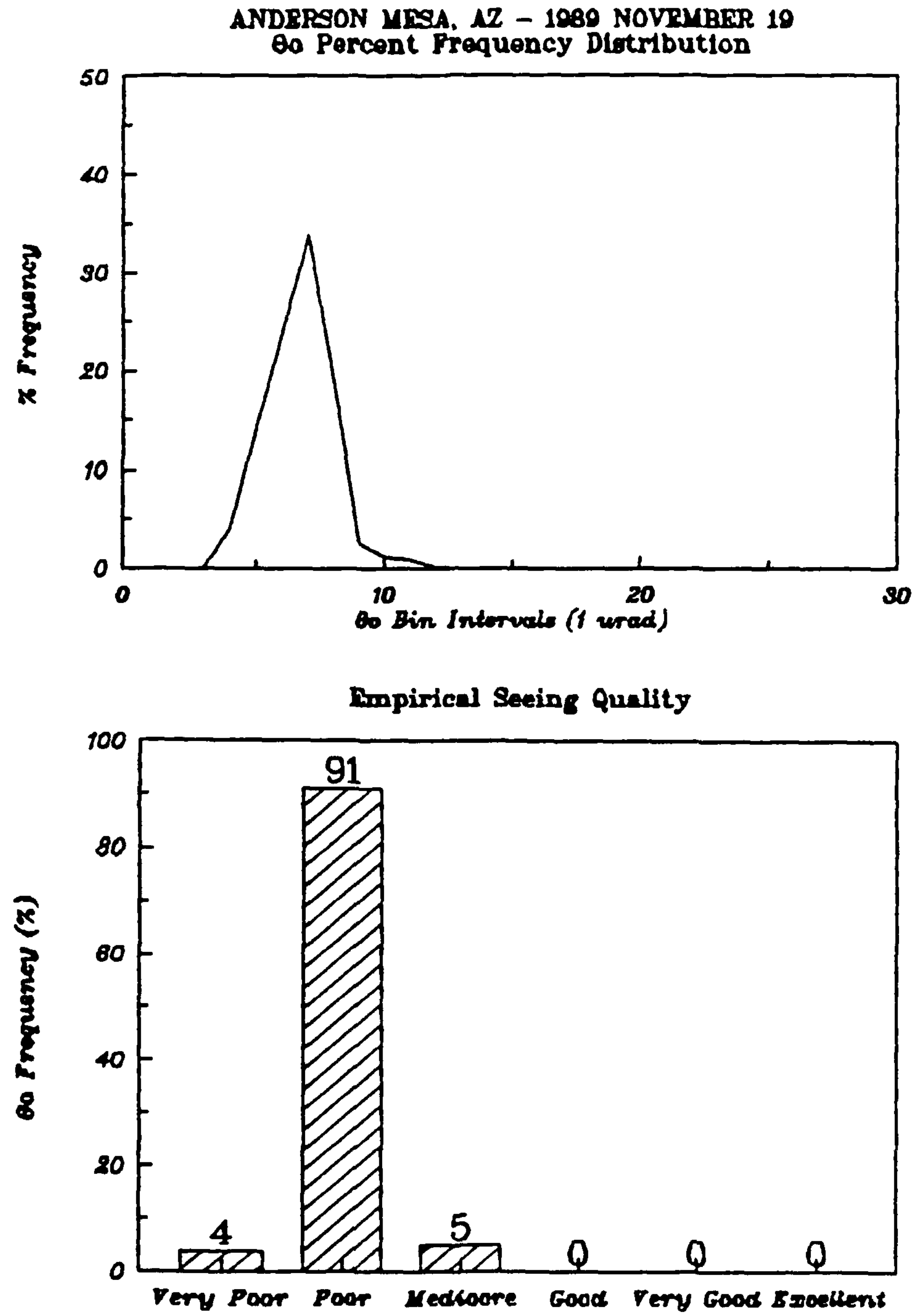


Fig 41. Anderson Mesa, Az θ_o Statistics: 1989 Nov 19

APPENDIX F. SEPTEMBER/NOVEMBER r_o AND θ_o DISTRIBUTION

Appendix F presents the cumulative September and November 1989 normalized frequency distribution for both r_o and θ_o . The measurements incorporated into these figures represent all the 17-28 September and 13-19 November 1989 processed NPS data taken at Anderson Mesa and the United States Naval Observatory near Flagstaff, Arizona. Specifically, Figure 42 displays the distribution generated from the 2,773 September and 2,103 November r_o samples. The 30,549 θ_o samples shown in Figure 43 includes: 16,355 September and 14,194 November individual angles.

CUMULATIVE NORMALIZED r_o FREQUENCY DISTRIBUTION
1989 September and November - Anderson Mesa, AZ

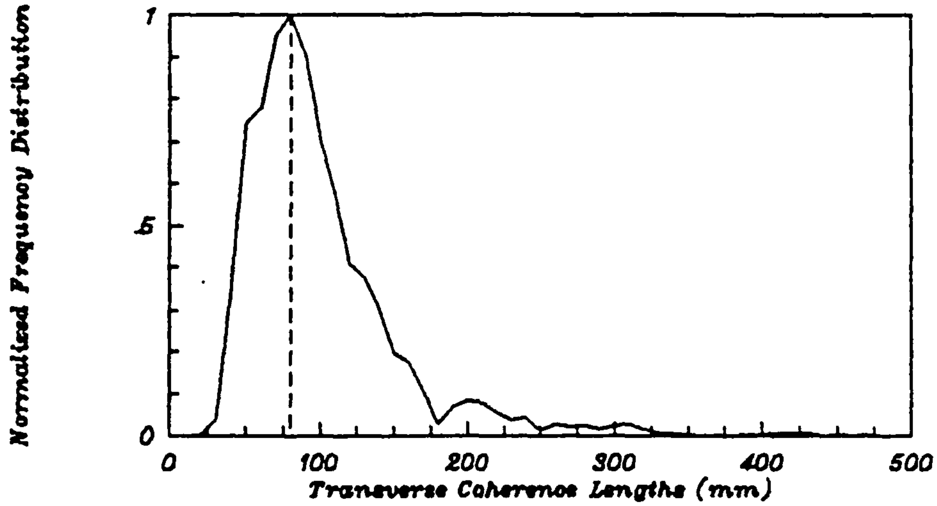


Fig 42. Cumulative r_o Distribution: 1989 Sept and Nov. The peak r_o bin interval is 80-90 mm.

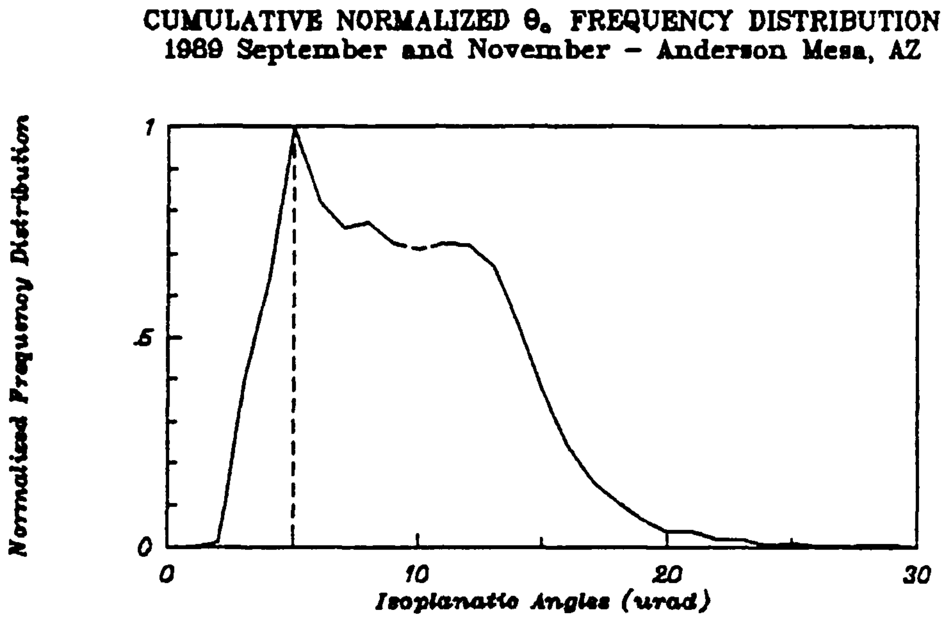


Fig 43. Cumulative Θ_o Distribution: 1989 Sept and Nov. The peak Θ_o bin interval is 5-6 urad.

LIST OF REFERENCES

Stevens, K.B., 1985: Remote Measurement of the Atmospheric Isoplanatic Angle and Determination of Refractive Turbulence Profiles by Direct Inversion of the Scintillation Amplitude Covariance Function with Tikhonov Regularization, Ph.D. Dissertation, Naval Postgraduate School, Monterey, CA, 170 pp.

Vaucher, G. Tirrell, 1989: Correlation of Atmospheric Optical Turbulence and Meteorological Measurements, M.S., Naval Postgraduate School, Monterey, CA, 145 pp.

Vaucher, G. Tirrell, Vaucher, Christopher A., Walters, Donald L., 1990: Optical Turbulence and Rawinsonde Measurements for 17-28 September 1989 at Anderson Mesa/United States Naval Observatory, Flagstaff, Arizona, Project Report No. NPS-61-90-005PR, Naval Postgraduate School, Monterey, CA, 105 pp.

Walters, D.L., Favier, D.L., and Hines, J.R., 1979: Vertical Path Atmospheric MTF Measurements. J. Opt. Soc. Am., v. 69, 829.

WeatherMeasure WEATHERtronics, 1987: 1987-1988 Catalog, Geophysical Instruments and Systems, Division of QUALIMETRICS, INC., Sacramento, CA, 323 pp.

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